Chapter 11

HYDROLOGIC METHODS AND COMPUTATIONS

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11.0 INTRODUCTION

Hydrology is the study of the properties, distribution, and effects of water on the earth's surface, and in the soils, underlying rocks, and atmosphere. The elements of the hydrologic cycle that will be discussed in this Chapter are the statistical rainfall patterns and the response characteristics of the natural and developed landscapes.

The hydrologic cycle is very complex. Simulating even a small portion of it, such as the relationship between precipitation and surface runoff, can be an inexact science. Many variables and dynamic relationships must be accounted for and, in most cases, reduced to basic assumptions. Many of these assumptions have been incorporated into past regulatory and computational frameworks for managing stormwater, in an effort to establish criteria that are relatively simple to implement. Unfortunately, either as a result of these assumptions or in spite of them, the resulting stormwater designs often do not meet all the program goals. As discussed in **Chapter 10** of this Handbook, the increases in the volume, duration, and frequency of peak runoff events have continued to impact streams and aquatic resources.

The Virginia Stormwater Management Program (VSMP) regulations (**4 VAC 50-60**) attempt to address these stormwater impacts by adopting the Virginia Runoff Reduction Method (VRRM). Using this method, the preferred compliance approach will now be to manage (and reduce to the extent possible) the volume of runoff from the most frequent rainfall events as the basis for hydrologic and hydraulic designs of stormwater management strategies. In general terms, this represents the incorporation of Better Site Design strategies (otherwise referred to as Low Impact development, Green Infrastructure, Environmental Site Design, etc.) into a regulatory framework built around runoff volume reduction. It should be understood that, as with past regulations, the reduction of pollutant loads remains the chief compliance metric. The difference is that runoff volume reduction is now an important, and in some cases necessary, strategy to achieve the required pollutant load reductions. Runoff volume reduction is also linked with revised channel and flood protection criteria in the VSMP regulations.

There is still a need to model the peak discharge and hydrologic and hydraulic response characteristics of the developed watershed. However, as discussed in **Chapter 10**, the hierarchy of treatment objectives to achieve the runoff water quality requirements starts with runoff volume reduction. The volume reduction, as tabulated through the VRRM, can then be applied to the quantity control strategies.

These same principles of volume reduction and the regulatory compliance criteria regarding pollutant removal are applied to the requirements of development on prior developed lands (i.e., redevelopment).

The purpose of this chapter is to provide background regarding volume reduction, a basic review of the hydrologic principles, and the computational procedures that apply to the VSMP regulations. This Chapter will build on the basic hydrologic and hydraulic stormwater management calculations provided in Chapters 4 and 5 of the Virginia Stormwater Management Handbook, First Edition, 1999 (***Blue Book***). Specific sections of the *Blue Book* are referenced in this chapter (rather than repeating the information), and the reader is encouraged to access the

Blue Book chapters, which will be kept on the VDCR website as legacy guidance, for a more detailed explanation or derivation of these calculations.

11.1 PRECIPITATION – NOAA ATLAS 14

Precipitation is a random event that cannot be predicted with certainty based on historical data. However, any given precipitation event has several distinct and independent characteristics which can be quantified as follows:

Duration - The length of time over which precipitation occurs (hours).
Depth - The amount of precipitation occurring throughout the storm duration (inches).
Frequency - The recurrence interval of events having the same duration and volume.
Intensity - The depth divided by the duration (inches per hour).

The statistical recurrence interval of these rainfall characteristics is the universal basis for most of the design criteria of the Virginia Stormwater Program:

- A 1-year frequency storm event is the combined rainfall characteristics of **depth** and **duration** that have a statistical probability of occurring at least once in any given year.
- The recurrence frequencies of rainfall intensities and durations provide the basis for the Rational Method computation of peak discharge using the **Intensity-Duration-Frequency** (IDF) Curves.
- Linear regression of the IDF curves described above provide the **"a" and "b" constants** used for the Modified Rational Method Critical Storm duration direct solution.

While it is true that precipitation is random and the amount of rainfall next week can't be predicted by the rainfall that occurred last week, there are predictive models that can look at years of rainfall records and predict future rainfall patterns. The longer the period of record that is considered, the more accurate the statistical analysis will be. This is especially true as we observe changing precipitation patterns (**Chapter 4.3**); the most recent rainfall data will reflect these changes to the extent possible.

The basis for the rainfall depths, frequencies, and intensities used for design must now reference the National Oceanographic and Atmospheric Administration (NOAA) Atlas 14 "Precipitation-Frequency Atlas of the United States" Volume 2, Version 3.0 (NOAA Atlas 14). Similarly, any continuous simulation models (**Section 4.2.5 of Chapter 4, *Blue Book***) should also use this source for the latest available rainfall data.

> **NOTE:** The VSMP regulation (**4 VAC 50-60-72 A**) identifies the required design storms as follows: *Unless otherwise specified, the prescribed design storms are the one-year, two-year, and 10-year 24-hour storms using the site-specific rainfall precipitation frequency data recommended by the U.S. National Oceanic and Atmospheric Administration (NOAA) Atlas 14.*

NOAA Atlas 14 rainfall data are based on significantly more data than the previous data set (Technical Paper 40). Technical Paper 40 used data through 1958, whereas NOAA Atlas 14 uses data through 2000, vastly increasing the amount of data available. The NOAA Atlas 14 rainfall data provides the basis for the NRCS 24-hour rainfall depths used to apply to the Type II Rainfall Distribution (Type III in portions of southeast Virginia) [1] and unit runoff hydrographs for computing peak discharges. These data were also used to generate new IDF curves for use with the Rational Method [2], and new "a" and "b" constants for use in the Modified Rational Method direct solution.

Appendix 11-B provides the NOAA Atlas 14 rainfall data in tabular form for the 1, 2, 5, 10, 25, 50, and 100-year return frequencies. Some counties may have two (or more) rainfall zones (based on geography and regional rainfall influences). Therefore the tabular form will list "Zone 1", "Zone 2", etc. **Figures 11.B-1** through **11-B.17** provide maps of those counties so designers can determine which rainfall depths are appropriate for the location of the project. For example, **Figure 11.1** represents the four rainfall zones in Carroll County, Virginia.

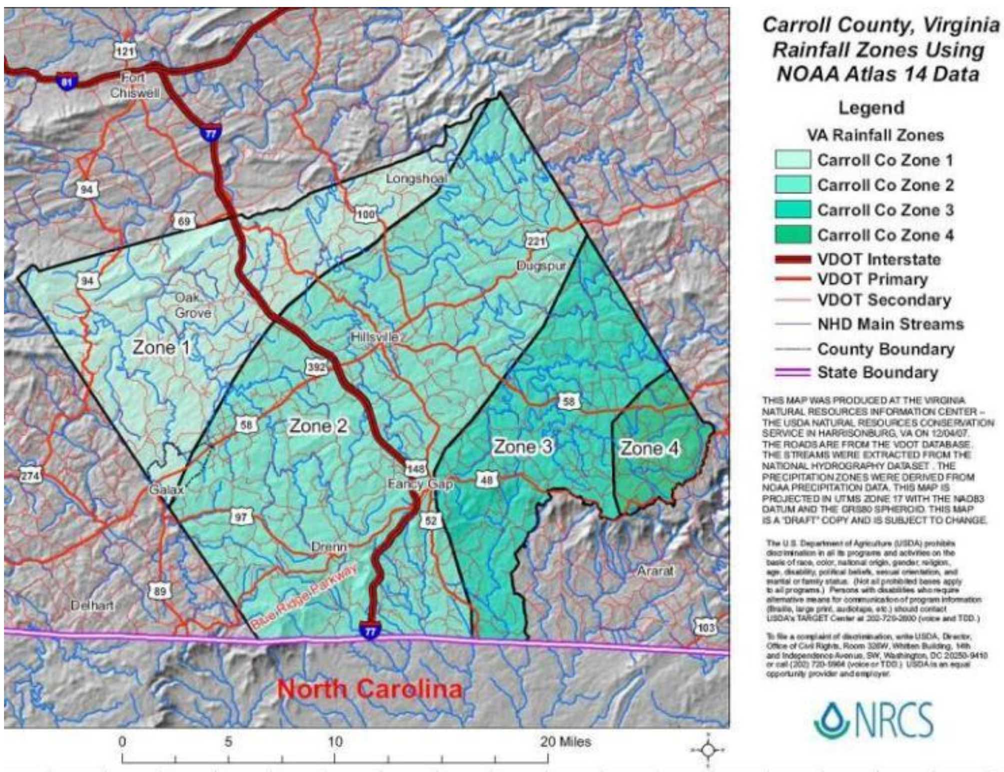

Figure 11.1. NOAA Atlas 14 Data Rainfall Zones for Carroll County, VA

[1] NRCS has advised that the NOAA Atlas 14 rainfall data may not follow the current Type II and Type III temporal rainfall distribution curves and should be used with caution for storms greater than the 10-year event. New software for TR-55, TR-20, and EFH-2 will be developed that will convert the Atlas 14 data to county-specific temporal distribution curves.

[2] To simplify the access and use of the new IDF Curves generated by Atlas 14 generated rainfall data, VDOT has developed a set of "B, D, & E" factors for each county and major city throughout the Commonwealth for the 2, 5, 10, 25, 50, & 100-yr recurrence interval storm durations, found in Appendices 6C-1 and 6C-2 in Chapter 6 of the VDOT Drainage Manual, at:
http://www.extranet.vdot.state.va.us/locdes/electronic%20pubs/2002%20Drainage%20Manual/pdf/drain-manual-chapter-06.pdf

11.2 24-HOUR RAINFALL DISTRIBUTION AND RUNOFF HYDROGRAPHS

The NRCS 24-hour storm distribution curve was derived from the National Weather Bureau's Rainfall Frequency Atlases. Further detailed discussion of the derivation and application of the 24-hour rainfall distribution used to generate a runoff hydrograph is provided in **Section 4-2.3** of **Chapter 4** of the ***Blue Book***, and Section 4 (Hydrology) of the USDA-NRCS's *National Engineering Handbook* (NRCS NEH). The reader will also find a detailed discussion of NRCS Runoff Hydrographs, including unit hydrographs and synthetic hydrographs in **Section 4-3** of **Chapter 4** of the ***Blue Book***.

There have been numerous studies of small storm hydrology and the potential for underestimating runoff using the NRCS Runoff Equation (Pitt, 1999). However, the small storm based provisions of the VSMP regulations (**4 VAC 50-60-65. Water Quality Compliance**) requires the use of the VRRM to manage a Treatment Volume (*Tv*) that is calculated using a rainfall depth and volumetric runoff coefficients (*Rv*), and not the NRCS Runoff Equation. The VRRM and *Tv* are described in more detail in **Section 11.4** of this chapter.

Section 4 VAC 50-60-72.C of the VSMP regulation, covering design storms and hydrologic methods, states the following:

> *The U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) synthetic 24-hour rainfall distribution and models, including, but not limited to TR-55 and TR-20; hydrologic and hydraulic methods developed by the U.S. Army Corps of Engineers; or other standard hydrologic and hydraulic methods, shall be used to conduct the analyses described in this part.*

The regulation goes on to allow the use of the Rational and Modified Rational Methods, since these are commonly used methods (**4 VAC 50-60-72 D & E**):

> *D. For drainage areas of 200 acres or less, the stormwater program administrative authority may allow for the use of the Rational Method for evaluating peak discharges.*
> *E. For drainage areas of 200 acres or less, the stormwater program administrative authority may allow for the use of the Modified Rational Method for evaluating volumetric flows to stormwater conveyances.*

The reader should note that the volume reduction credit that applies to the VSMP Quantity Control requirements (**4 VAC 50-60-66**) has been developed to readily apply to NRCS methodology using the NRCS Runoff Equation (**Section 11.6** of this chapter). Further, the Rational Method has traditionally been used for computing peak discharges for sizing pipes and drainage conveyance infrastructure, for which the upper acreage threshold of 200 acres may be appropriate. However, there are limitations on the appropriateness of the Rational and Modified Rational Methods as stormwater management sizing and compliance tools. These methods, as well as the NRCS method, and their applicability and limitations are described below.

11.3 RUNOFF AND PEAK DISCHARGE

The practice of estimating runoff as a fixed percentage of rainfall has been used in the design of storm drainage systems for over 100 years. Despite its simplification of the complex rainfall-runoff processes, it is still the most commonly used method for urban drainage calculations. It can be accurate when drainage area land cover is highly impervious and/or homogeneous.

For urbanizing watersheds or drainage areas comprised of pervious cover such as open space, woods, lawns, or agricultural land uses, with varying amounts of impervious cover mixed in throughout the entire area, the rainfall/runoff relationship becomes much more complex.

In very general terms, hydrologic methods can be grouped by their capability to effectively model the land uses, combine the flows from distinct drainage areas, and provide the output in a format applicable to stormwater design. This section will provide a very brief overview of the methods acknowledged in the VSMP regulations: the Rational Method, the Modified Rational Method, and NRCS Methods. The NRCS Methods include numerous modeling and predictive techniques. However, the use of the NRCS basic hydrologic principles of Curve Number (*CN*), Time of Concentration (*Tc*), and a runoff hydrograph and peak discharge are covered here as described in *Technical Release 55: Urban Hydrology for Small Watersheds*. (NRCS, 1986).

As mentioned previously, the reader is also encouraged to review **Section 4-4** of **Chapter 4** of the ***Blue Book*** for additional detail and applicability of these methods.

11.3.1 Rational Method

The ***Rational Method*** was introduced in 1880 as a way to determine peak discharges from drainage areas. It is frequently criticized for its simplistic approach, but this same simplicity has made the Rational Method one of the most widely used techniques today for calculating peak discharge from urban land uses.

The Rational Formula estimates the peak rate of runoff at any location in a drainage area as a function of the *runoff coefficient*, *mean rainfall intensity*, and *drainage area*. The ***Rational Formula*** is expressed as follows:

Equation 11.1. Rational Formula

$$Q = CIA$$

Where:

Q = maximum rate of runoff (cfs)

C = dimensionless runoff coefficient, dependent upon land use (refer to **Section 4-4.1** in **Chapter 4** of the ***Blue Book*** for reference to acceptable runoff coefficients).

I = design rainfall intensity (in./hr.), for a duration equal to the time of concentration of the watershed

A = drainage area (acres)

As with all hydrologic methods, there are numerous assumptions related to the rainfall duration and intensity as a function of the drainage area size. Given the highly impervious urban landscape origins of the Rational Method, it is logical to establish that under steady rainfall the peak discharge occurs once the entire drainage area is contributing to the point of study. This occurs at a time (t) equal to the Time of Concentration (Tc). Since the method was developed only to predict the maximum peak discharge, the continuation of rainfall – in theory – does not cause any increase in peak rate of discharge. **Figure 11.2** illustrates a Rational Method runoff hydrograph.

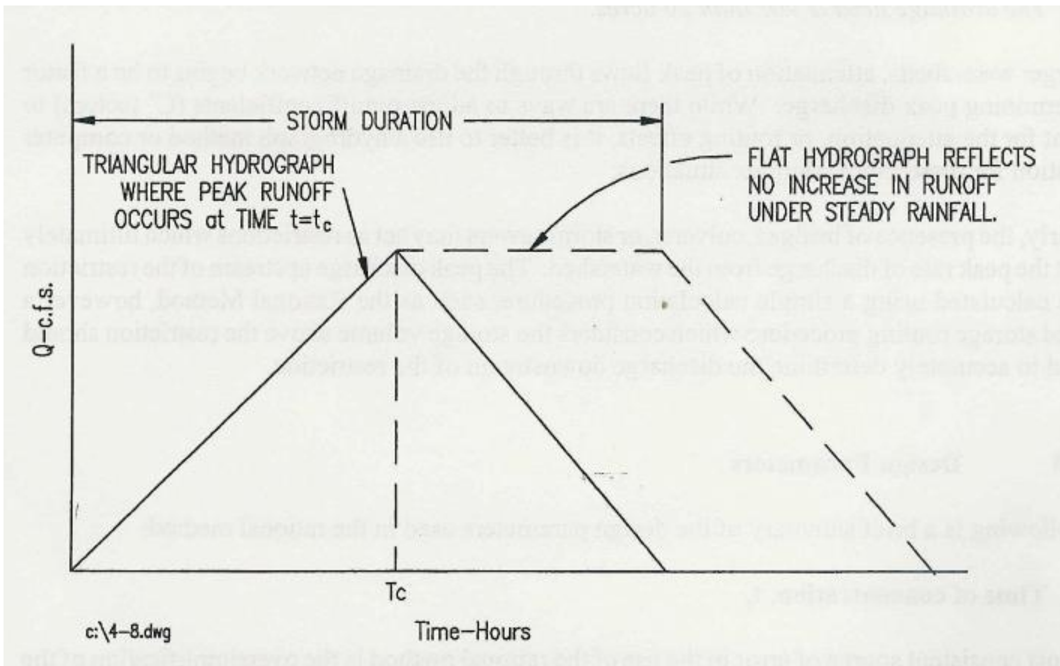

Figure 11.2. Rational Method Runoff Hydrograph

An important and possibly limiting factor is the lack of a true runoff hydrograph. As stated, the method was developed to predict peak flow rates occurring when the entire drainage area is contributing runoff. Establishing an arbitrary storm duration that is considered equal to the Tc, or some longer duration, can create a simple runoff hydrograph (in this case in the shape of a triangular or trapezoidal shape). However, the critical elements are not related to rainfall or land use patterns other than the intensity of the rainfall maximum return frequency. This may be appropriate for calculating a peak discharge, but it is arbitrary in terms of a total volume of runoff (defined as the area under the triangular or trapezoidal hydrograph shown in **Figure 11.2**). Quantifying the volume of runoff is important in demonstrating compliance with the VSMP quantity control requirements.

Based on these factors, and others described in **Section 4-4.1** of **Chapter 4** of the ***Blue Book*** , the use of the Rational Method as a hydrologic method for stormwater management facility design is typically limited as follows:

1. *The contributing drainage area is highly impervious;*
2. *The contributing drainage area has a time of concentration, Tc, less than 20 minutes; and*
3. *The contributing drainage area is less than 20 acres.*

> **Note:** This guidance contradicts the allowed upper limit of 200 acres (VSMP Authority option) provided in **4 VAC 50-60-72.D** & **E**, as noted above**.** Designers should verify the VSMP Authority requirements regarding acceptance of this or other hydrologic methods for demonstrating compliance with the VSMP regulations.

When using the Rational Method, the designer will no longer use the IDF curves to determine the rainfall intensity for the calculated Tc. Instead, the designer should refer to the "B, D, & E" factors for each county and major city throughout the Commonwealth for the 2, 5, 10, 25, 50, & 100-year recurrence interval storm durations (Tc) (NOTE: B, D, & E factors are not available for the 1-year design storm). As noted above, the B, D, & E factors were derived from the NOAA Atlas 14 rainfall data by VDOT and are published by VDOT in the VDOT Drainage Manual Appendix 6C-1 and 6C-2 at:

http://www.extranet.vdot.state.va.us/locdes/electronic%20pubs/2002%20Drainage%20Manual/pdf/drain-manual-chapter-06.pdf (revised 7/09)

The values are used to compute the rainfall intensity I (inches/hour) as follows:

Equation 11.2 Rational Method Rainfall Intensity

$$I_f = \frac{B}{(T_c + D)^E}$$

Where:

I_f = Rainfall intensity for a given year recurrence interval (2, 5, 10, 25, 50, & 100-year) in inches/hour

T_c = Drainage area time of concentration assumed equal to the storm duration), in minutes

11.3.2 Modified Rational Method: Critical Storm Duration

The modified rational method is a variation of the Rational Method, developed mainly for the sizing of detention facilities in urban areas. The Modified Rational Method is applied in a manner similar to that of the Rational Method, except that it uses a fixed rainfall duration. The Rational Method generates the peak discharge that occurs when the entire watershed is contributing to the peak (at a time $t = Tc$) of a triangular hydrograph and ignores the effects of a storm which lasts longer than time t. The modified rational method, on the other hand, considers storms with a longer duration than the watershed Tc, which may result in a smaller or larger *peak rate of discharge*, but will produce a greater *volume* of runoff (area under the triangular or trapezoidal hydrograph) associated with the longer duration of rainfall. **Figure 11.3** below shows a family of hydrographs representing storms of different durations.

> **NOTE:** The storm duration which generates the greatest volume of runoff may not necessarily produce the greatest peak rate of discharge.

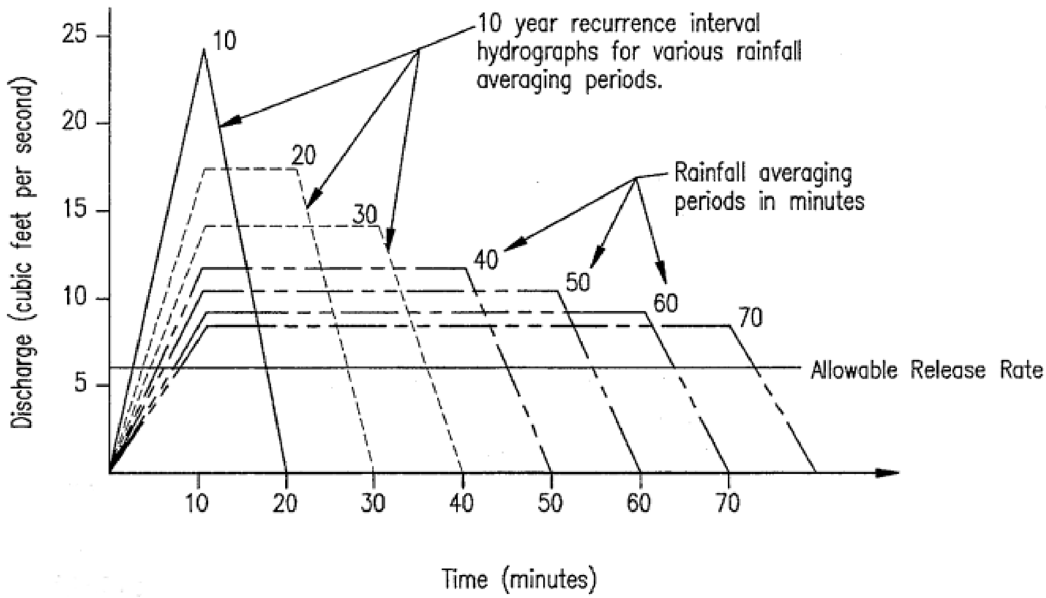

Figure 11.3. Modified Rational Method Family of Runoff Hydrographs

All of the limitations listed for the Rational Method also apply to the Modified Rational Method. The key difference is the assumed shape of the resulting runoff hydrograph. The modified rational method allows the designer to analyze several different storm durations to determine the one that requires the greatest storage volume with respect to the allowable release rate. This storm duration is referred to as the ***critical storm duration*** and is used as a basin sizing tool. The technique is discussed in more detail in **Section 4-4.2** of **Chapter 4** of the *Blue Book* .

The designer might perform an iterative calculation to determine the rainfall duration which produces the maximum storage volume requirement when sizing a detention basin. Or, a simpler approach would be to calculate the Modified Rational Method Critical Storm Duration Direct Solution which uses rainfall "a" and "b" constants. These constants have been updated to reflect the NOAA Atlas 14 rainfall data, however, there are no values for the 1-year storm event and therefore may not be applicable to the VSMP channel protection criteria. A detailed explanation of the computational procedure is provided in **Section 5-4.3** of **Chapter 5** of the *Blue Book.* The updated "a" and "b" constants can be found in the VDOT Drainage Manual Appendix 11-H-1 and 11H-2 at:

http://www.extranet.vdot.state.va.us/locdes/electronic%20pubs/2002%20Drainage%20Manual/pdf/drain-manual-chapter-11.pdf (revised 7/09)

Chapter 11.5.4.2 of the VDOT Drainage Manual provides important usage instructions for the "a" and "b" constants.

11.3.3 NRCS Methods

The USDA-Natural Resource Conservation Service (NRCS) published Technical Release Number 55 (TR-55), 2nd edition, in June of 1986, entitled *Urban Hydrology for Small Watersheds*. The techniques outlined in *TR-55* require the same basic data as the rational method: drainage area, time of concentration, land use and rainfall. The NRCS approach, however, is more sophisticated in that it allows the designer to manipulate the time distribution of the rainfall, the initial rainfall losses to interception and depression storage, and the moisture condition of the soils prior to the storm. **Section 4-4.3** of **Chapter 4** of the ***Blue Book*** provides a detailed description of these variables.

TR-55 presents two general methods for estimating peak discharges from urban watersheds: the **graphical method** (see **Section 4-4.4** of **Chapter 4** of the ***Blue Book***) and the **tabular method** (see **Section 4-4.5** of **Chapter 4** of the ***Blue Book***). The graphical method is limited to watersheds whose runoff characteristics are fairly uniform and whose soils, land use, and ground cover can be represented by a single Runoff Curve Number (*CN*).

The tabular method is a more complete approach and can be used to develop a runoff hydrograph at any point in a watershed. For large watersheds, it may be necessary to divide the area into sub-watersheds in order to account for major land use changes, analyze specific study points within sub-watersheds, or locate stormwater drainage facilities and assess their effects on peak flows. ***The tabular method can generate a hydrograph for each sub-watershed for the same storm event***. The hydrographs can then be ***routed*** through the watershed and combined to produce a partial composite hydrograph at the selected study point. ***The tabular method is particularly useful in evaluating the effects of an altered land use in a specific area within a given watershed***.

> **NOTE:** As noted above, the NRCS tabular method is presented in the ***Blue Book*** and referenced here in an effort to distinguish the difference between the graphical peak discharge and tabular hydrograph methods. The tabular method of developing a runoff hydrograph is relatively straight forward, yet cumbersome when attempted long-hand (pencil and paper), much like the storage indication routing technique outlined in **Section 5-9** (*Hydrograph Routing*) of **Chapter 5** of the ***Blue Book***. While both these methods are straightforward, computing them long-hand is comparable to using an abacus or a slide rule to compute standard engineering calculations. VSMP Authority site plan reviewers are not likely to encounter a plan using either the long-hand TR-55 Tabular Hydrograph Method or long-hand Storage Indication Routing in the final stormwater design computations.
>
> In most cases, the designer will use the NRCS methods to develop the base hydrology (*CN*, *Tc*, graphical peak discharge [q_p], etc.), and use that data in one of the numerous hydrologic/hydraulic computer models (including TR-55, TR-20, HEC 1, etc.).

The NRCS methods of graphical peak discharge are covered in detail in ***Blue Book*** and will not be repeated in the same detail here, other than to describe how they apply to the VRRM. The reader is strongly encouraged to obtain a copy of the *TR-55* manual from the USDA-NRCS to gain more insight into the procedures and limitations.

11.3.4 NRCS Curve Number and Runoff Depth

Prior to using either the graphical or tabular methods to calculate a peak discharge, the designer must determine the watershed weighted *CN* and the *Tc*. The NRCS *CN* is used to develop the rainfall-runoff relationship and estimate the depth of runoff (*Q*) in inches. This method is described in detail in **Section 4** of the NRCS *National Engineering Handbook (NEH*, NRCS, 1985). The *runoff equation* (found in *TR-55* and discussed later in this section) provides a relationship between rainfall and runoff as a function of the *CN*. The *CN* is a measure of the land's ability to infiltrate or otherwise detain rainfall, with the excess becoming runoff. The *CN* is a function of the land cover (woods, pasture, agricultural use, percent impervious, etc.), hydrologic condition, and soils.

The VSMP regulations address the development of the rainfall-runoff relationship very specifically in **4 VAC 50-60-66 Water Quantity**:

> *E. For purposes of computing predevelopment runoff, all pervious lands on the site shall be assumed to be in good hydrologic condition in accordance with the U.S. Department of Agriculture's Natural Resources Conservation Service (NRCS) standards, regardless of conditions existing at the time of computation. Predevelopment runoff calculations utilizing other hydrologic conditions may be utilized provided that it is demonstrated to and approved by the VSMP authority that actual site conditions warrant such considerations.*
> *F. Predevelopment and postdevelopment runoff characteristics and site hydrology shall be verified by site inspections, topographic surveys, available soil mapping or studies, and calculations consistent with good engineering practices. Guidance provided in the Virginia Stormwater Management Handbook and by the Virginia Stormwater BMP Clearinghouse shall be considered appropriate practices.*

This regulatory language clearly places significant emphasis on accurate field reconnaissance to verify the information needed to develop a *CN* for both the pre- and post-development conditions. While it may seem arbitrary that the pre-development land cover must be considered to be in “good” condition, the premise is that if it is not in good condition, this is likely due to some form of land disturbance or use and, therefore, not reflective of true *pre-development* conditions.

<u>Curve Number:</u> *Section F* of the VSMP regulations noted above identifies the level of effort required to collect the data needed to establish the *CN*:

1. Soils mapping (to determine the hydrologic soil group): **Section 4-4.3.3** of **Chapter 4** of the ***Blue Book*** provides a detailed description of the NRCS Hydrologic Soil Group (HSG)

Classification. **Appendix 11-A** of this chapter provides a list of the HSG classifications for the soils of Virginia.
2. Land cover type (impervious, woods, grass, etc.).
3. Treatment (cultivated or agricultural land).
4. Hydrologic condition (for design purposes, the hydrologic condition should be considered "GOOD" for the pre-development condition).
5. Urban impervious area modifications (connected, unconnected, etc.).
6. Topography – detailed enough to accurately identify drainage divides, t_c and T_t flow paths and channel geometry, and surface condition (roughness coefficient).

NOTE: **Terminology Alert 1 – It is very important to recognize that TR-55 and the VRRM use the term *Open Space* differently**:

- The VRRM considers *managed turf* to be equivalent to the TR-55 *open space*, that is: lawns, parks, golf courses, and cemeteries, with a *CN* equivalent to pasture/grassland in good hydrologic condition. This generally represents lawn areas that have been cleared and/or graded to accommodate development.
- The VRRM considers *Open Space* to be protected undisturbed (or restored) land comparable to *Forest* and equivalent to the TR-55 *woods*, that is: wooded areas protected from grazing with ground litter and brush covering the soil.

The VRRM definition of what can be considered *Forest/Open Space* is provided in **Table 12.1** of **Chapter 12** of this Handbook, and includes land that will remain undisturbed OR that will be restored to a hydrologically functional state; as well as land that will be subject to minimal operational and management activities so as to minimize the compaction of soils, the application of fertilizers, and other impacts. In all cases, the designation of lands as *Forest/Open Space* will require some form of a protective covenant.

The designer should refer to **Chapter 4** of the ***Blue Book*** or more appropriately TR-55 for a full explanation of the basis for NRCS *CN*'s.

Runoff Depth Q: The runoff depth is the measure of the fraction of rainfall that becomes runoff. The NRCS runoff equation (TR-55 2-1) is used to solve for runoff depth, Q, in inches, as a function of rainfall depth and *CN*:

Equation 11.3. NRCS Runoff Equation, Q *[TR-55 Eq. 2-1]*

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S}$$

Equation 11.4. NRCS Runoff Equation, Ia *[TR-55 Eq. 2-2]*

$$I_a = 0.2S$$

Equation 11.5. Modified NRCS Runoff Equation *[TR-55 Eq. 2-3]*

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

Equation 11.6. NRCS Runoff Equation: S *[TR-55 Eq. 2-4]*

$$S = \frac{1000}{CN} - 10$$

Where: Q = runoff depth (in),
P = rainfall depth (in),
I_a = Initial abstraction (in),
S = potential maximum retention after runoff begins (in),
CN = Curve Number

These terms are further described, as follows:

- The Runoff Depth (Q) is measured in inches and can also be referred to in units of watershed-inches, meaning it represents the depth of runoff across the watershed or drainage area as described by the *CN*, and can easily be converted into a volume of runoff. (The runoff equation figures prominently in the application of the volume reduction credit when applied to the quantity control requirements; see **Section 11.6** of this Chapter.)

  NOTE: Terminology Alert Number 2 – the term ***Q*** is often used in stormwater designs to refer to peak discharge measured in cubic feet per second (***cfs***). However, NRCS methodology uses ***Q*** to refer to runoff depth, in inches, as noted in the NRCS Runoff Equation above. The runoff depth is readily converted to runoff volume by multiplying by the drainage area, or is converted to peak discharge (***q***, measured in units of cubic feet per second, or ***cfs***) through a process of convolution using a unit hydrograph or the TR-55 Graphical Peak Discharge method.

  The VRRM Compliance Spreadsheet's *Channel and Flood Protection* tab uses the term ***RV*** for the Runoff Depth in inches as applied to the *CN* adjustment. Further discussion of the VSMP regulation Quantity Control Criteria will require further clarification of these terms (see **Section 11.6.1** of this Chapter).

- The rainfall (P) as required by the VSMP regulations is as follows:
  - 1-inch of rainfall is determined to be the 90th percentile rainfall depth, required by the VRRM to address the annual pollutant load reduction requirements (**4 VAC 50-60-65 Water Quality Compliance**). The determination of the 90th percentile rainfall is discussed in more detail in **Section 10.1.2** of **Chapter 10** of this Handbook**;** or

- 1-year 24-hour storm, 2-year 24-hour storm, and/or the 10-year 24-hour storm rainfall depths, as derived from NOAA Atlas 14 (**Appendix 11-B**) as required for addressing the water quantity (stream channel and flood protection) requirements (**4 VAC 50-60-66. Water Quantity**).

- Initial abstraction (*Ia*) is the combination of all rainfall losses before runoff begins, and consists mainly of interception, infiltration during early parts of the storm, and surface depression storage. It is measured in inches and can be described as the depth of rainfall that occurs before runoff begins. Infiltration during the early part of the storm is highly variable and dependent on such factors as rainfall intensity, soil crusting, and soil moisture (antecedent condition); however, it is generally correlated with soil and land cover parameters. Values for *Ia* can be obtained in TR-55.
- The potential maximum retention (*S*) after runoff begins is dependent upon the soil cover complex and, in principle, should not vary from storm to storm. It is the depth of rainfall that is captured and retained on the landscape in excess of the initial abstraction. **The application of Runoff Reduction practices serves to increase the maximum retention (*S*), thereby decreasing the *CN*** (discussed further in **Section 11.6.3** of this Chapter).

TR-55 provides a graphical solution for the runoff equation, provided in **Appendix 11-C**. Also, the National Engineering Handbook provides the runoff depths for selected *CNs* in tabular form, also provided in **Appendix 11-C**. Additional information on the derivation, assumptions, and limitations of the Runoff Equation can be found in Section 4 of the NRCS *National Engineering Handbook.*

11.4 THE VIRGINIA RUNOFF REDUCTION METHOD

The Virginia Runoff Reduction Method (VRRM) is designed to provide a more consistent path towards achieving the water quality treatment objectives (nutrient reductions) and performance goals (annual load reductions) as identified by the VSMP regulations: the reduction of nutrients, specifically Total Phosphorus (TP), to a prescribed site-based annual pollutant load limit (TP ≤ 0.41 lb/ac). (see **Section 11.4.4** of this Chapter)

Previous stormwater quality regulatory performance goals were focused, figuratively speaking, on scrubbing the target pollutants out of each drop of storm water with the application of BMPs. This strategy is dependent on the BMP's ability to reduce the Event Mean Concentration (EMC in mg/l) of the pollutant in the runoff. The challenges with this strategy have become very apparent:

- BMP performance is highly variable. Nutrient removal, especially TP and TN, can be very difficult to target and quantify based on seasonal and other factors;
- Nutrients in the natural environment can exist in different forms and at a wide range of concentrations. In some circumstances, it may be physically impossible, using BMPs only, to consistently reduce the EMC of any given pollutant to the extent required by the VSMP regulations or that which may be required to meet water quality goals. For many pollutants, the outflow from a BMP is limited by the threshold of an "irreducible concentration," which is reflective of the limits of the treatment mechanisms.

Therefore, the VRRM adds the reduction of runoff volume as an important treatment objective, representing a significant means to achieve the primary compliance objective of pollutant removal. In theory, where BMPs may not be able to consistently reduce the EMC of a pollutant (the amount of pollutant in each drop of water), the runoff reduction strategies aim to reduce the total number of drops of runoff, thereby dramatically improving the total annual pollutant load reduction performance. This overall performance can be characterized as follows:

Total Load Reduction (TR) lb/yr = Runoff Reduction (RR) + Pollutant Removal (PR)

Another primary goal of the VRRM is to establish a link between the water quality and water quantity requirements of the regualtions. The Code of Virginia (§ 10.1-603.4. Development of regulations) establishes that the VSMP regulations should encourage the use of Low Impact Development. While not actually mandating specific site design strategies, the VRRM incorporates provisions that allow the designer to compute the hydrologic credit of incorporating structural and nonstructural volume reduction water quality protection strategies and, by doing so, to reduce the storage volume required to meet the water quantity (channel and flood protection) requirements.

Chapters 5 and **6** of this Handbook provide extensive amounts of information related to stormwater management approaches and site design strategies that reduce stormwater volume. The VRRM Technical Memo (CWP 2008) provides the supporting documentation for the runoff reduction capabilities and updated pollutant removal performance of the different BMPs. **Section 11.6** of this chapter provides information on crediting runoff volume reduction for water quantity control requirements.

11.4.1 The Virginia Runoff Reduction Method as a Regulatory Standard

Section **4 VAC 50-60-65.A** of the VSMP regulation requires that:

> *A. Compliance with the water quality design criteria set out in subdivisions 1 and 2 of 4 VAC 50-60-63 shall be determined by utilizing the Virginia Runoff Reduction Method or another equivalent methodology that is approved by the board.*
>
> *B. The BMPs listed below are approved for use as necessary to effectively reduce the phosphorus load and runoff volume in accordance with the Virginia Runoff Reduction Method.*

This establishes the VRRM as the computational method for demonstrating compliance (however, the Board may authorize the use of an "equivalent" methodology). **Section 4 VAC 50-60-63**, referred to in the citation above, establishes the water quality design criteria requirements; and the reference to the "BMPs listed" establishes that BMPs listed on the Virginia BMP Clearinghouse website are the practices authorized to be used for compliance.

The VRRM represents a simple computational method that establishes specific values for several fundamental parameters of stormwater management. These parameters, listed below, represent the core functional elements of the method:

1. Volumetric runoff coefficients for three basic land cover types (undisturbed forest/open space; disturbed areas/managed turf; and impervious cover) based on Hydrologic Soil Groups.

   The volumetric runoff coefficients (*Rv*) are discussed in detail in the VRRM Technical Memo (CWP 2008), and **Section 5.3.2** of **Chapter 5** and **Section 10.1.2.1** of **Chapter 10** of this Handbook. These coefficients, based on extensive research, reflect the relative contributions of the different land covers to both runoff volume and runoff pollutant loads.

   > **NOTE**: **Terminology Alert 3 – This *Rv* term should not be confused with the VSMP regulation Channel Protection Criteria Energy Balance Equation term for runoff volume , labeled as *RV*. Refer to Table 11.3 in Section 11.6.1 of this Chapter.**

2. Computational procedures for determining the BMP design Treatment Volume (*Tv*) using the 90^{th} percentile rainfall depth.

   The *Tv* is a central component of the VRRM and represents the common currency of site-based stormwater management, linking the water quality and quantity criteria together. The *Tv* and the establishment of the 90^{th} percentile rainfall depth is discussed in more detail in **Section 5.3.3** of **Chapter 5** and **Section 10.1.2** of **Chapter 10** of this Handbook.

3. Computational procedure for calculating annual pollutant loading from a developed site; Simple method.

   The VRRM uses a modified Simple Method (**Equation 11.9, Section 11.4.4**) for calculating the annual pollutant load from the developed site. The calculation is performed for the entire site to establish the target load reduction requirement, and for each drainage area to determine the relative reduction achieved by the implementation of BMPs. The load reduction achieved through the implementation of structural and nonstructural BMPs must be such that the calculated site-based total annual load is less than or equal to 0.41 lb/ac/yr (**4 VAC 50-60-63.A.1**).

4. Runoff reduction and pollutant removal credits for specific BMPs (the sizing of which are governed by the BMP Design Specifications approved by Director of the Department of Environmental Quality [DEQ] and posted on the Virginia BMP Clearinghouse website);

   The VRRM Technical Memo (CWP 2008) identifies the research that supports the BMP pollutant removal and volume reduction credits adopted by the DEQ. The basis of the BMP design specifications, including the Level 1 and Level 2 designs and performance credits, includes a thorough review of the National Stormwater Quality Database (NSQD 2004), the National Pollutant Removal Performance Database (version 3 (CWP, 2007), and a literature review and synthesis of 50 stormwater technical notes and in-depth analysis of more than 70

BMP research studies. Level 1 and Level 2 BMP standards are discussed further in **Section 11.4.3** of this Chapter.

5. Computational procedures are provided for a simplified *CN* adjustment to account for runoff reduction practices when evaluating compliance with the water quantity control requirements (channel and flood protection) of **4 VAC 50-60-66**.

   Several methods of manipulating the large storm runoff hydrograph to reflect the runoff reduction achieved in meeting the water quality requirements were considered. The *CN* adjustment was considered a reasonable estimation of the runoff hydrograph, and is covered in more detail in **Section 11.6.3** of this Chapter.

11.4.2 Volumetric Runoff Coefficients (*Rv*)

Chapter 5.3.4 describes the VRRM three-step compliance strategy. The compliance objective is still to meet the site-based pollutant load limit for Total Phosphorus. Therefore, the three-step strategy represents the suggested means to achieve that load limit, beginning with site design and runoff reduction practices. In that context, the regulatory requirement is not to incorporate all three steps for every development site. Depending on site characteristics and load reduction requirements, a site may incorporate one, two, or all three of the steps. Nevertheless, the three steps are a sound way to start developing a compliance strategy. The three steps are as follows:

Step 1: Apply Environmental Site Design (ESD)practices to minimize impervious cover, grading, and loss of forest cover. This step includes the conservation of open spaces where the natural soil horizon and native vegetation is preserved. Employing these practices can result in a reduction of the required water quality Treatment Volume (*Tv*) and pollutant load generated by the site, *before any BMPs are selected and applied to the site design*.

Step 2: Apply Runoff Reduction (RR) BMPs to reduce the runoff volume generated by the developed portions of the site. This step includes the selection of those BMPs that have demonstrated the ability to retain runoff volume through evapotranspiration, infiltration, extended filtration, and alternative use (such as rainwater harvesting). This step also includes the restoration or the protection of established hydrologically functional areas of the site, such as buffers, conserved open space, reforested areas, addition of soil amendments, etc.; and

Step 3: Apply Pollutant Removal (PR) BMPs to achieve any remaining pollutant removal that may be required to achieve the required annual load limit of 0.41 lb/ac. This step can also include the purchase of nutrient offsets or other off-site compliance options.

The primary objective of Step 1 is to reduce the overall site runoff volume. The computational equivalent would be to reduce the runoff depth (*Q*) described in **Section 11.3.4**. In some cases, the implementation of ESD practices will be self-crediting; that is, designs that reduce impervious cover and/or maintain forested areas will have a lower *CN* and thereby a lower overall runoff depth computed, using the NRCS Runoff Equation. Likewise, the VRRM computational procedure for computing the annual pollutant load and the corresponding runoff *Tv* for BMP sizing will self-credit when areas of the site are undisturbed or designated for restoration and/or protection. **Table 11.1** provides the relevant volumetric runoff coefficients (*Rv*).

Table 11.1. Land Cover Volumetric Runoff Coefficients (Rv)

Land Cover	**Runoff Coefficients**			
	HSG-A	**HSG-B**	**HSG-C**	**HSG-D**
Forest/Open Space	0.02	0.03	0.04	0.05
Disturbed Soil or Managed Turf	0.15	0.20	0.22	0.25
Impervious Cover	0.95			

Source: CWP, 2008

As illustrated by the *Rv* values in **Table 11.1**, the effect of grading, site disturbance, and soil compaction greatly increases the runoff coefficient compared to forested areas. These values are based on research (CWP, 2008) that includes small storm hydrology factors in order to correlate the 1-inch rainfall event to an annual volume of runoff. That is, by managing the runoff from the 1-inch rainfall event, the total annual volume of rainfall that is managed can be translated to an equivalent annual volume of runoff and pollutant load computation.

The designer will enter the acres of *Forest/Open Space*, *Managed Turf*, and *Impervious Cover* into the User Input cells of the Site Data tab and the appropriate drainage area (D.A.) tabs of the VRRM Compliance Spreadsheet. The spreadsheet will generate a composite *Rv* for the site and the drainage areas. This composite *Rv* is comparable to a NRCS *CN* or the Rational Method runoff coefficient in that it describes how much rainfall becomes runoff.

The proper assignment of *Rv* values to the different land covers requires that the designer have accurate soil information for the site. Another element in selecting *Rv* values is verifying that any acreage that is to be designated as *Forest/Open Space* will in fact be preserved, both during construction and after construction. This means that these areas must be designated to be protected on the erosion and sediment control plan, and an enforceable recorded protective documentation (e.g., easement) must be developed and executed prior to plan approval.

11.4.3 Treatment Volume (Tv)

Treatment Volume (*Tv*) is the calculated design volume of runoff that must be managed to meet the VSMP water quality requirements. The VSMP water quality load limit for TP is a site-based limit, meaning that the *Tv* does not need to be "zeroed out." The *Tv* is reduced to the point where the site-base load limit is achieved. In other words, if enough total load reduction (TR) is achieved through runoff reduction (RR), Pollutant removal (PR), or a combination of the two in one portion of the site or drainage area, the remaining area does not require treatment. (On the other hand, every point of stormwater discharge from the site must be analyzed to show compliance with the VSMP water quantity requirements.)

> **NOTE: Terminology Alert Number 4 –** The term Treatment Volume (*Tv*) refers to the volume associated with a particular drainage or land area based on the land cover and resulting volumetric Runoff Coefficient (*Rv* – see **Section 11.4.2**). There can be a *Tv* for the entire site (based on the composite Runoff Coefficient), a *Tv* for a particular drainage area within the site (for instance, for each drainage area tab in the VRRM Compliance Spreadsheet), and a *Tv* for an individual BMP based on the contributing drainage area and/or volume from an upstream practice. These can be referred to as $Tv_{SITE,}$ $Tv_{DA,}$ and Tv_{BMP} respectively.
>
> It is important to note that the Tv_{SITE} is the most important for overall compliance purposes, as it relates directly to computing the post-developed pollutant load and the corresponding load reduction required to meet the site-based TP load limit. Any adjustments to a Drainage Area tab land cover based on the site design BMP selection, i.e., the selection of a BMP such as *Sheetflow to a Vegetated Area or Open Space*, or preservation of open space or reforestation should also be reflected on the Site Data tab land cover, as this will reduce the overall site-based reduction requirement.
>
> The Tv_{BMP} is most important for sizing individual BMPs in accordance with the specifications, because each BMP is sized based on the *Tv* generated by the contributing drainage area (CDA) draining to that BMP.

Most of the BMP Design Specifications include a Level 1 and Level 2 design standard. The Level 1 standard generally requires a storage or treatment function sized for the *Tv*. The Level 2 design standard increases the *Tv* storage or treatment function sizing by a factor of 1.1, 1.25, or 1.5. This *Tv* multiplier is included in the BMP Design Specifications and was derived for each practice based on the available BMP performance data relative to the annual volume of runoff treated. (Refer to the complete BMP Design Specifications posted on the Virginia Stormwater BMP Clearinghouse website at: http://vwrrc.vt.edu/swc/.)

The VRRM *Tv* is calculated by multiplying the 1-inch rainfall depth by the composite *Rv* based on the three site cover runoff coefficients: *Forest/Open Space* (*F*), *Managed Turf* (*T*), and *Impervious Cover* (*I*) present at the site, as shown in **Equation 11.7** below (CWP et al., 2008). This method generates a *Tv* of close to 1 inch for highly impervious sites and a gradually decreasing *Tv* for decreasing levels of imperviousness.

Equation 11.7 Stormwater Treatment Volume (Tv)

$$Tv = \frac{P \times [Rv_{composite}] \times SA}{12}$$

Equation 11.8 Composite Volumetric Runoff Coefficient ($Rv_{composite}$)

$$Rv_{composite} = (Rv_I \times \%I) + (Rv_T \times \%T) + (Rv_F \times \%F)$$

Where:

Tv =	Stormwater treatment volume in acre feet
$Rv_{composite}$ =	Composite or weighted runoff coefficient
P =	Depth of rainfall; "water quality" P = 1-inch
RvI =	Runoff coefficient for Impervious cover (Table 11.1)
RvT =	Runoff coefficient for Turf cover or disturbed soils (Table 11.1)
RvF =	Runoff coefficient for Forest/Open Space (Table 11.1)
$\% I$ =	Percent of site in Impervious cover (fraction)
$\%T$ =	Percent of site in Turf cover (fraction)
$\%F$ =	Percent of site in Forest/Open Space (fraction)
SA =	Total site area, in acres

As discussed in **Terminology Alert Number 4** above, this computation can be for the site, a drainage area within the site, or an individual BMP drainage area.

Related to the discussion of *CN* in **Section 11.3.4** of this Chapter, another important terminology alert is provided here to emphasize the importance of proper land cover definitions associated with the VRRM:

> **NOTE**: **Terminology Alert Number 5** – TR-55 and the VRRM use the term Open Space differently:
>
> - The VRRM considers *managed turf* to be equivalent to the TR-55 *open space*, that is: lawns, parks, golf courses, and cemeteries, with a *CN* equivalent to pasture/grassland in good hydrologic condition. This generally represents lawn areas that have been cleared and/or graded to accommodate development.
> - The VRRM considers *Open Space* to be protected undisturbed (or restored) land comparable to *Forest* and equivalent to the TR-55 *woods in good hydrologic condition*; that is, wooded areas protected from grazing with ground litter and brush covering the soil.
> - The VRRM definition of what can be considered *Forest/Open Space* is provided in **Table 12.1** o*f* ***Chapt*****er 12**, and includes land that will remain undisturbed OR that will be restored to a hydrologically functional state, as well as land that will be subject to minimal operational *and management* activities so a**s to minimize the compaction of soils**, the application of fertilizers, and other impacts. In all cases, the designation of lands as *Forest/Open Space* will require some form of a permanent protective covenant, deed restriction, easement, or similar measure.

The designer should refer to **Chapter 4** of the ***Blue Book*** or, more appropriately TR-55 for a full explanation of the basis for the *CN*s, and **Table 12.1** of **Chapter 12-** for de*tails and definit*ions on how to qualify land cover for purposes of calculating the *Tv*.

11.4.4 The Simple Method

The Simple Method estimates the annual pollutant load exported in stormwater runoff from small urban catchments (Schueler, 1987). The Simple Method sacrifices some precision for the sake of simplicity and ease of use, but it is a reasonably accurate way to predict annual pollutant loads. The Simple Method as shown in **Equation 11.9** below was used to establish the site-based annual TP load limit of 0.41 lb/ac/yr (average natural load), and is also used to calculate the annual TP and TN loads of the site in its developed condition (Site Data tab of the VRRM Compliance Spreadsheet). The difference between these two TP values represents the site-based TP Load reduction requirement.

Equation 11.9 Simple Method Pollutant Load Calculation

$$L = P \times P_i \times Rv_{composite} \times C \times A \times 2.72/12$$

Where:

L = total post-development pollutant load (pounds/ year)
P = average annual rainfall depth (inches) = 43 inches for Virginia
P_j = fraction of rainfall events that produce runoff = 0.9
$Rv_{composite}$ = composite volumetric runoff coefficient (**Equation 11.8**)
C = flow-weighted event mean concentration (EMC) of TP (mg/L)
A = area of the development site (acres)
12 = unit conversion factor: rainfall inches to feet
2.72 = unit conversion factor: L to ft^3, mg to lb, and acres to ft^2

The VRRM Compliance Spreadsheet also calculates the pollutant load generated by the contributing drainage area to the selected BMPs (D.A. tabs). Refer to **Chapter 12** of this Handbook for an explanation of the VRRM Compliance Spreadsheet and the supporting calculations.

11.4.4.1 Total Phosphorus Event Mean Concentration

The Center for Watershed Protection (CWP) analyzed the National Stormwater Quality Database (NSQD) version 1.1 to compare Virginia with National Event Mean Concentrations (EMCs) derived for total nitrogen (TN), total phosphorus (TP), and total suspended solids (TSS). Statistical trends were examined for the EMCs based on land use (residential/non-residential) and physiographic province (Piedmont/Coastal Plain).

Based on the analysis, there is a statistically significant difference in pollutant concentrations in stormwater between residential and nonresidential sites, particularly for TN. In one sense, this could have been considered justification for using different EMCs for the two categories of land use. However, the designation of a land use category would also require a corresponding impervious cover in order to differentiate between high density residential and commercial, detached residential and campus commercial, etc. The distinction of the amount of impervious cover created unintended consequences, including hidden incentives to increase impervious cover to qualify for an easier compliance threshold, among other complications. This ultimately led to the selection of a single EMC standard for measuring compliance.

The review of Virginia piedmont and coastal plain residential and non-residential EMCs bracketed the existing standard of 0.26 mg/l as established by the Virginia Stormwater Management Program (CWP 2008). Therefore, the TP EMC for regulatory compliance remains 0.26 mg/l.

11.4.4.2 Site-Based Total Phosphorus Load Limit

The site-based load limit for TP was derived with the intention of establishing the allowable maximum TP load from developed lands that would meet the targets established in the Virginia Tributary Strategies. As the Chesapeake Bay Total Maximum Daily Load Watershed Implementation Plan (TMDL WIP) came to replace the earlier Virginia tributary strategies, the focus on setting this site-based load limit shifted towards identifying the land being converted to development. Several iterations of calculations were considered, each making different assumptions of the land conversions: the relative amount of forest and agricultural lands historically being converted to urban lands.

The Chesapeake Bay TMDL WIP initially identified that the allocation for nutrient loads from new developed lands would be based on achieving no increase above allowable 2025 average nutrient loads from previous land uses. The final TMDL Phase I WIP further refined the proposed load limit by establishing that the assumed “previous” or prior land uses of the proposed developed lands within Virginia’s Chesapeake Bay watershed would be assumed to be a mix of forest, cropland, pasture, and hay.

A Virginia Stormwater Management Regulatory Advisory Panel (RAP) was convened to analyze the various options previously considered, as well as propose new ones, for establishing a land-use based regulatory nutrient load limit for new development. The RAP considered several scenarios of land use conversion trends in the Chesapeake Bay watershed (WSSI, 2001a). Since the regulatory mandate was intended to apply statewide, the focus was adjusted to consider all of Virginia and not just the Chesapeake Bay watershed. Ultimately the RAP elected to use the Impervious Cover Model (Schueler et al. 2009) to define the nutrient baseline upper limit as that generated by the amount of impervious cover that has been shown to impact the index of biotic integrity in streams: approximately 5% to 10% small watershed imperviousness. Since the VRRM also identifies the other land covers associated with urban development as sources of TP, the RAP also had to designate the base-line upper limit land cover for the balance of the developed site: *managed turf* and *forest/open space* and the corresponding soil types (since the VRRM runoff coefficients are adjusted for hydrologic soil groups).

The final consensus of the RAP was to define the target site-based load limit from newly developed lands as **0.41 lb/ac/yr**, computed using the VRRM for typical land cover as follows:

Impervious cover = 10%
Forest/Open Space = 60%
Managed Turf = 30%

The assumed soil types for each land cover were estimated from the from STATSGO state-wide soils database soils breakdown for Virginia outside of the Chesapeake Bay Watershed:

HSG A:	1.15%	HSG C:	28.60%
HSG B:	61.28%	HSG D:	8.97%

11.5 WATER QUALITY CALCULATIONS

Water quality calculations include the steps of calculating the pollutant loading from the developed site (**Equation 11.9**), and developing a combined strategy of site design and BMP implementation that reduces the calculated pollutant load to the required load limit of 0.41 lb/ac (**Equation 11.10**). The selection and design of various site design and BMP strategies can be tested using the VRRM Compliance spreadsheet. The basis of the VRRM is the use of site design strategies that increase runoff abstraction and the implementation of stormwater BMPs that include retention storage to reduce the volume of runoff discharging from the site as a pathway to reduce pollutant loads. Additional pollutant load reduction can be achieved with BMPs that do not necessarily retain runoff. The volume and pollutant reduction credit is combined as a percent reduction and applied to the calculated pollutant load (**Equation 11.9**) to demonstrate compliance with the site based load limit. **Equation 11.10** provides the computation for the pollutant load reduction requirement. The BMP implementation strategy must achieve a total load reduction (runoff volume reduction plus pollutant removal) efficiency to achieve the required reduction.

Equation 11.10: Water Quality Pollutant Load Reduction Requirement

$$L_{reduction} = L_{postdevelopment} - (0.41\, lb/ac/yr) \times A$$

Where:

$L_{reduction}$	= load reduction requirement (lb)
$L_{postdevelopment}$	= postdevelopment pollutant load (**Equation 11.9**)
0.41 *lb/ac/yr*	= site based TP load limit
A	= drainage or site area (acres)

11.5.1 General Considerations: Stormwater Retention vs. Detention

The definition of retention storage implies infiltration, evapotranspiration, or use (as in rainwater harvesting). The most common example of retention is infiltration. However, the physical ability to infiltrate runoff into the native soil horizon is limited by the permeability of the native soil. While runoff will naturally seep into even hydrologically limited soils (such as HSG C and D soils) if given enough time, the typical stormwater management strategy of conveying the runoff from a developed drainage area to a comparatively small area designated for infiltration is limited by the hydrologic and hydraulic loading of the soils. In other words, relying on infiltration in marginal soils (i.e., with low permeability) as a long term stormwater retention strategy, even when implementing uniformly distributed micro-scale practices, is highly dependent on adequate soil permeability in order to meet requirements for long term performance.

The challenge of ensuring that the operational life of retention BMPs is comparable to that of the other site infrastructure is best addressed during design. Many designers elect to forego infiltration (unless the soils are verified as highly permeable, and the site is relatively clean, i.e., low traffic and minimal particulate pollutant loads) and instead select practices that include an underdrain.

The popularity of bioretention as a stormwater practice can be partially attributed to its effectiveness in providing the function of retention through the engineered soil media, along with the biological uptake and evapotranspiration through the plantings, even with an underdrain [3]. The Level 1 and some Level 2 practices that incorporate an underdrain provide varying degrees of volume reduction credit. Some credit is derived from the internal water storage within the soil matrix where the volume of runoff is held for an extended period (and either released by the plants via evapotranspiration or eventually drained by the underdrain) and the Level 2 credit is partially attributed to the potential for infiltration at the bottom of the practice (infiltration sump). Research indicates that the delayed discharge from bioretention cells is statistically similar to storm flow reaching streams via interflow in undeveloped watersheds (DeBusk et al. 2011).

These results suggest that a bioretention cell with an underdrain processes stormwater and delivers it to the receiving stream in a manner comparable to an undeveloped watershed, particularly in watersheds that don't exhibit naturally high levels of infiltration. As such, the retention credit is applied to practices with an underdrain based on mimicking the pre-development hydrologic characteristics of interflow. **Section 8.1** of **Chapter 8** provides additional research and supporting documentation for the various runoff volume reduction mechanisms, including evapotranspiration.

Another distinction between retention and detention is the availability of storage for additional runoff over an extended storm event. It should be expected that, once filled, the traditional retention storage is no longer available to capture additional runoff volume. For storm events greater than 1 inch or consecutive rain events with a short interval, runoff will likely bypass the practice; whereas practices with underdrains will likely have some storage capacity available as runoff is leaving the system over the course of the storm. This results in treatment of more volume than the static design storage. This might seem to be contrary to the statements above regarding retention; however, it actually is consistent with how an undeveloped watershed processes stormwater as the soils begin to saturate, creating more runoff.

11.5.2 BMP Sizing Using the VRRM Treatment Volume

The VSMP regulations require an *annual* pollutant load reduction. To achieve this performance goal, the 90th percentile rainfall depth of 1 inch was selected as the design storm for sizing

[3] The Level 2 Bioretention design includes a provision for establishing a sump beneath the underdrain in order to achieve Level 2 performance even with an underdrain.

BMPs. The rationale for using the 90th percentile event is that it represents the majority of runoff volume on an annual basis, and that targeting larger events would not be cost effective in terms of BMP implementation. The upward inflection of the rainfall depth-frequency curve at the 90% mark (**Chapter 10, Figure 10.3**) indicates that BMPs would be required to be increasingly larger and more expensive for every incremental increase in rainfall depth above 1 inch. However, targeting the first 1-inch rainfall depth still provides partial treatment for water quality and quantity protection for these larger storms. **Chapter 10** provides a thorough explanation of the choice of the1-inch rainfall depth as the water quality design storm.

The Post-Development *Tv* (**Equation 11.7**) is computed in the VRRM Compliance Spreadsheet:

1. On the Site Data tab for the entire site (Tv_{SITE});
2. For each drainage area on the D.A. tabs (Tv_{DA}); and
3. For each BMP selected in the D.A. tab, based on the Credit Area of *turf acres* and *impervious acres* draining to the practice (Tv_{BMP}). **This is the *Tv* that is used to size the BMP**.

The Tv_{BMP} used to size the BMP (item 3 above), **is not summed for the designer in the VRRM Compliance Spreadsheet**. Rather, the designer has to determine the design Tv_{BMP} by summing the Runoff Reduction (D.A. tab Column I) and the Remaining Runoff Volume (D.A. tab Column J). This sum also includes the additional runoff volume (if any) delivered from an upstream practice (Column H). Or the designer may use **Equation 11.7** to compute the volume independent of the spreadsheet.

Example *Tv* determination: The following example illustrates the determination of the Tv_{BMP} from the D.A. tab of the VRRM Compliance Spreadsheet.

Step 1: Consider a drainage area of 2.5 acres within a larger development site:

Drainage Area Land Cover data input cells:

Drainage Area A Land Cover (acres)						
	A soils	**B Soils**	**C Soils**	**D Soils**	**Totals**	**Land Cover Rv**
Forest/Open Space (acres)	0.00	0.00	0.50	0.00	0.50	0.04
Managed Turf (acres)	0.00	0.00	0.75	0.00	0.75	0.22
Impervious Cover (acres)	0.00	0.00	1.25	0.00	1.25	0.95
				Total	2.50	

Post Development Treatment Volume (cf)	4,982

Step 2: Determine the contributing drainage area of Managed Turf and Impervious cover to a selected BMP. Any area of *Forest/Open space* to the BMP is not applied to BMP sizing (this is intended to avoid the need to construct BMPs to manage runoff from *Forest/Open Space*, it also serves as an incentive to avoid impacting forested areas, and to protect or restore new open space areas).

Select Bioretention Level 1:

Treat all the impervious acres [1.25 ac (row 46, column G)]; and all the turf acres [0.75 ac (cell G47)]

Treatment Volume (*Tv_{BMP}*) to Bioretention Level 1:

Sum of cells I46 and I47 (Runoff Reduction: 1,724 + 240) & J46 and J47 (Remaining Runoff Volume: 2,586 + 359) = **4,909 ft^3**

Total Area Treated (cells G71 and G72) = 1.25 ac impervious, 0.75 ac turf

Bioretention Level 1 is treating 2.0 acres, and is sized based on a contributing Tv_{BMP} of **4,909 ft^3**.

This example can also illustrate how the design Tv_{BMP} being directed to the Bioretention BMP is reduced when the contributing drainage area, or a portion thereof, is directed to a runoff reduction BMP prior to the Bioretention area. In this case, an **Alternate Scenario** includes Permeable Pavement Level 1 to treat a portion of the parking runoff prior to discharging to Bioretention.

Alternate Scenario:

Step 1: Manage some of the parking runoff (0.75 ac of the 1.25 acre of impervious) with Permeable Pavement Level 1; and direct the remaining runoff to a downstream Bioretention Level 1 practice (that will also treat the remaining impervious area and all the turf acres – **Step 2** below).

Select Permeable Pavement Level 1:

Implement 0.75 acres of permeable pavement [0.75 ac (cell G28)];

Treatment Volume (*Tv_{BMP}*) to Permeable Pavement L1:

Sum of cell I28 (Runoff Reduction: 1,164) & J28 (Remaining Runoff Volume: 1,423) = **2,587 ft^3**

Select Bioretention Level 1 as Downstream Treatment to be Employed (column P).

Step 2: **Select Bioretention L1**: Treat the <u>remaining</u> impervious acres [1.25 – 0.75 = 0.5 ac (cell G46)]; and all the turf acres [0.75 ac (cell G47)] with Bioretention L1.

Treatment Volume (*Tv_{BMP}*) to Bioretention L1:

Sum of cells I46 and I47 (Runoff Reduction: 1,259 + 240) & J46 and J47 (Remaining Runoff Volume: 1,888 + 359) = **3,746 ft^3** (reduction of approximately 24% of the required Bioretention *Tv*).

The total Tv_{BMP} includes 1,423 ft^3 of Volume from Upstream RR Practice (cell H46)

Total Area Treated (cells G71 and G72) = 1.25 ac impervious, 0.75 ac turf.
The same acreage is treated, however the design treatment volume to the Bioretention Level 1 is reduced, and the overall pollutant load reduction performance is increased by using an upstream practice to create a volume reduction treatment train.

11.5.2.1 Annual Volume and Pollutant Load Reduction Credit

The VRRM Compliance Spreadsheet is a BMP selection and *compliance* tool – not a BMP design tool. It provides a common language and allows for cross-checking between designers and plan reviewers. The discussion above illustrates how the spreadsheet will provide valuable information regarding BMP sizing and design. It is important to note that, when a BMP such as Bioretention is selected, the spreadsheet does not include a sizing or *"storage volume provided"* function. As such, the *annual* volume and pollutant load reduction computation does not reflect BMP sizing; the spreadsheet assumes that the BMP has been sized according to the BMP Design Specifications, and awards the annual volume reduction credit accordingly. There is no increase in the annual volume or pollutant load reduction (other than that awarded for Level 2) since there is no supporting data for the load reductions associated with the small number of storms that represent the largest 10% of the annual rainfall events.

Similarly, the quantity control credits that are applied to the *CN* adjustment calculations on the Spreadsheet's Channel and Flood Protection tab do not reflect instances of increased storage. The Curve Number adjustment represents the blending of *annual* volume reduction and *single-event* modeling in the VRRM. The intent is to provide a practical and easy-to-use compliance tool, and not a design tool (which would be significantly more complex and likely not a spreadsheet based application).

NOTE: BMPs can be designed with additional storage volume above the required Level 1 or Level 2 design *Tv*. **However, sizing must still be in accordance with the BMP Specifications, and the *annual* volume and *annual* pollutant load reduction credit is not influenced by any increase in the sizing. The regulated pollutant load reduction credits itemized in the BMP Design Specifications are annual values, and compliance with the VSMP regulations are based on annual load reductions.**

As noted above, the VRRM Compliance Spreadsheet does not incorporate BMP sizing into the Curve Number adjustment when providing the volume credit towards quantity control requirements. If the designer wishes to use an oversized runoff reduction and/or water quality protection practice to achieve additional storage credit towards quantity control requirements, the calculations demonstrating the value of that additional volume must be performed independent of the VRRM compliance spreadsheet (such as a hydrologic or routing program). In other words, the spreadsheet will only compute the *CN* adjustment based on the annual volume reduction credit for a properly sized BMP.

11.5.2.2 BMP Design Volume

The sizing of Runoff Reduction BMPs will either include a storage volume or a surface area or other element that is created to accommodate the design Tv_{BMP} according to the various BMP Design Specifications. It is important to recognize that most BMPs incorporate a surface area design feature that, while not the primary sizing factor, is a critical design feature for ensuring BMP performance and longevity. This combined design element is identified in column 4 of **Table 11.2**.

An example of combined design elements the Bioretention specification, where the design is focused on providing an adequate total storage volume and surface area within the practice. This includes the storage volume elements of surface ponding volume within the soil media and gravel layers, and the additional requirement of establishing a minimum surface area in order to effectively manage the incoming volume and peak rate of runoff.

Table 11.2. Primary BMP Sizing, Design, and Compliance Features

BMP		Runoff Reduction and/or Pollutant Removal Credit Based on Storage Volume [1]	Runoff Reduction and/or Pollutant Removal Credit Based on Surface Area [2]	Design Criteria include both Storage Volume & Surface Area Components [3]
Sheet Flow to Conservation Areas			✓	
Sheet Flow to Vegetated Filter Strips			✓	
Simple Disconnection			✓	
Simple Disconnection with Compensatory Practices	**Micro-Infiltration**	✓		✓
	Residential Rain Garden	✓		✓
	Rainwater Harvesting	✓		
	Urban Planter	✓		✓
Bioretention		✓		✓
Permeable Pavement		✓		✓
Grass Swale		✓		✓
Infiltration		✓		✓
Rainwater Harvesting		✓		
Vegetated Roof		✓		✓
Filtration		✓		✓
Extended Detention		✓		✓
Stormwater Wetlands			✓	✓

[1] Minimum design criteria for storage volume.
[2] Minimum design for surface area of the practice.
[3] Minimum design criteria include storage volume and surface area design features.

11.5.3 Water Quality Design *Tv* Peak Flow Rate

The peak flow rates for the 1-year 24-hour storm and larger storms are readily computed using accepted hydrologic methods outlined in this chapter. However, there has not been a standard method for computing the water quality design peak flow rate. The water quality design peak flow rate is needed for the design and sizing of pretreatment cells, level spreaders, by-pass diversion structures, overflow riser structures, grass swales and water quality swale geometry, etc. All require a peak rate of discharge in order to ensure non-erosive conditions and flow capacity.

Of the hydrologic methods available, the Rational Formula is highly sensitive to the time of concentration and rainfall intensity, and therefore should only be used with reliable Intensity-Duration-Frequency (IDF) curves (or B, D, & E factors discussed in **Section 11.3.1** on page 11-9 above) for the rainfall depth and region of interest (Claytor and Schueler, 1996). Unfortunately, there are no IDF curves or B, D, & E factors available for the 1-inch rainfall depth. The NRCS *CN* methods are very useful for characterizing complex sub-watersheds and drainage areas and estimating the peak discharge from large storms (greater than 2 inches), but can significantly underestimate the discharge from small storm events (Claytor and Schueler, 1996). Since the *Tv* is based on a 1-inch rainfall, this underestimation of peak discharge can lead to undersized diversion and overflow structures, resulting in a significant volume of the design *Tv* potentially bypassing the runoff reduction practice. Undersized overflow structures and outlet channels can cause erosion of the BMP conveyance features which can lead to costly and frequent maintenance.

In order to maintain consistency and accuracy, the following Modified *CN* Method is recommended to calculate the peak discharge for the 1-inch rain event. The method uses the Small Storm Hydrology Method (Pitt, 1994) and NRCS Graphical Peak Discharge Method (USDA, 1986) to provide an adjusted Curve Number that is more reflective of the runoff volume from impervious areas within the drainage area. The design rainfall is a NRCS Type II distribution, so the method incorporates the peak rainfall intensities common in the eastern United States. The time of concentration is computed using the method outlined in TR-55.

The following provides a step by step procedure for calculating the Water Quality Treatment Volume's peak rate of discharge, $\boldsymbol{q_{pTv}}$:

Step 1: Calculate the adjusted *CN* for the site or contributing drainage area.
The following equation is derived from the NRCS *CN* Method and is described in detail in the **Chapter 4** (Hydrology) of the National Engineering Handbook (NEH-4), and **Chapter 2** (Estimating Runoff) of NRCS TR-55:

Equation 11.11 Derivation of NRCS Curve Number and Runoff Equation

$$CN = \frac{1000}{[10 + 5P + 10Q_a - 10(Q_a^2 + 1.25Q_aP)^{0.5}]}$$

Where:

CN = Adjusted curve number
P = Rainfall (inches), (1.0” in Virginia)
Q_a = Runoff volume (watershed inches), equal to $Tv \div drainage\ area$

Note: When using a hydraulic/hydrologic model for sizing a runoff reduction BMP or calculating the q_{pTv}, designers must use this modified *CN* for the drainage area to generate runoff equal to the *Tv* for the 1-inch rainfall event.

Step 2: Compute the Time of Concentration (*Tc*) for the site or drainage area.
Chapter 4 of the ***Blue Book*** and Chapter 3 of TR-55 (Time of Concentration and Travel Time) provide detailed procedures for computing the *Tc.* The designer should select the *Tc* flow path that is representative of the impervious cover. .

Step 3: Calculate the Water Quality Treatment Volume’s peak discharge (q_{pTv})
The (q_{pTv}) is computed using the following equation and the procedures outlined in Chapter 4 (Graphical Peak Discharge Method) of TR-55.

Equation 11.12. Modified NRCS TR-55 Eq. 4-1

$$q_{pTv} = q_u \times A \times Q_a$$

Where:

q_{pTv} = Treatment Volume peak discharge (cfs)
q_u = unit peak discharge (cfs/mi^2/in)
A = drainage area (mi^2)
Q_a = runoff volume (watershed inches = Tv/A)

Designers can also use WinTR-55 or an equivalent TR-55 spreadsheet to compute (q_{pTv}):

- Read the initial abstraction (I_a) from TR-55 Table 4.1 or calculate it using $I_a = 200/CN - 2$
- Compute I_a/P (P = 1.0);
- Read the Unit Peak Discharge (q_u) from exhibit 4-II using *Tc* and I_a/P;
- Compute the (q_{pTv}) peak discharge:

This procedure is for computing the peak flow rate for the 1-inch rainfall event. All other calculations of peak discharge from larger storm events for the design of drainage systems, culverts, etc., should use published *CN*s and computational procedures.

11.5.4 On-Line and Off-Line BMPs

Runoff Reduction BMPs are typically sized and designed to manage the design treatment volume from the 1-inch rainfall event. In some cases designers may choose to manage or detain a larger storm event in order to partially or fully meet the quantity control requirements. In all cases, the designer must account for the conveyance of these larger storms *through* the BMP (the BMP is said to be ***On-Line***) or *around* the BMP (making the BMP ***Off-Line***).

Using the water quality design *Tv* peak flow rate described in **Section 11.5.3** above, the designer can size a bypass control for an *On-Line* BMP, such that flows that exceed the design capacity exit via an internal riser structure or weir overflow. This means that the BMP accepts all the runoff from the contributing drainage area and the overflow is within the BMP (or main treatment area). On-line BMPs must be carefully designed to accommodate the large storm design peak flow rate in terms of inflow velocity and energy, as well as an adequately sized overflow to allow the runoff to safely exit the BMP.

On-line systems in these cases will require careful design and construction to ensure adequate conveyance of the large storm inflow.

On-line systems should include the following:

- Inflow points should be protected from erosive velocity;
- An overflow structure must be provided within the practice to pass storms greater than the design storm storage to a stabilized conveyance or storm sewer system;
- Discharge from the overflow structure should be controlled so that velocities are non-erosive at the outlet point;

The overflow structure type and design should be scaled to the application – this may be a landscape grate or yard inlet for small practices or a commercial-type structure for larger installations.

Alternately, an *Off-Line* BMP design uses an external diversion structure to manage the large storm flow so the runoff in excess of the 1-inch rain event will not damage the BMP (excessive velocity or ponding depth) or re-suspend and export previously trapped pollutants. This can be accomplished through a low-flow diversion structure that channels the smaller storm flow volume into the BMP, while forcing the larger flows to bypass the BMP. These types of low-flow diversions or large storm bypass structures are external – thereby diverting the flow before it gets to the BMP – or they can be part of the BMP inlet structure, such as a forebay or level spreader. In some cases, off-line BMPs with a storage volume can be located so that once the storage volume is full, additional runoff simply diverts past or around the BMP. **Figure 11.4** below illustrates a simple off-line BMP.

Off-line designs require that the designer determine the runoff peak flow rates for the range of design storms: 1-inch rainfall depth, and 1-year, 2-year, and 10-year 24-hour storms, as needed. Off-line designs are usually the preferred option for volume reduction BMPs, especially where larger drainage areas (e.g., greater than 0.5 to 1 acre) are conveyed by a pipe or armored drainage system.

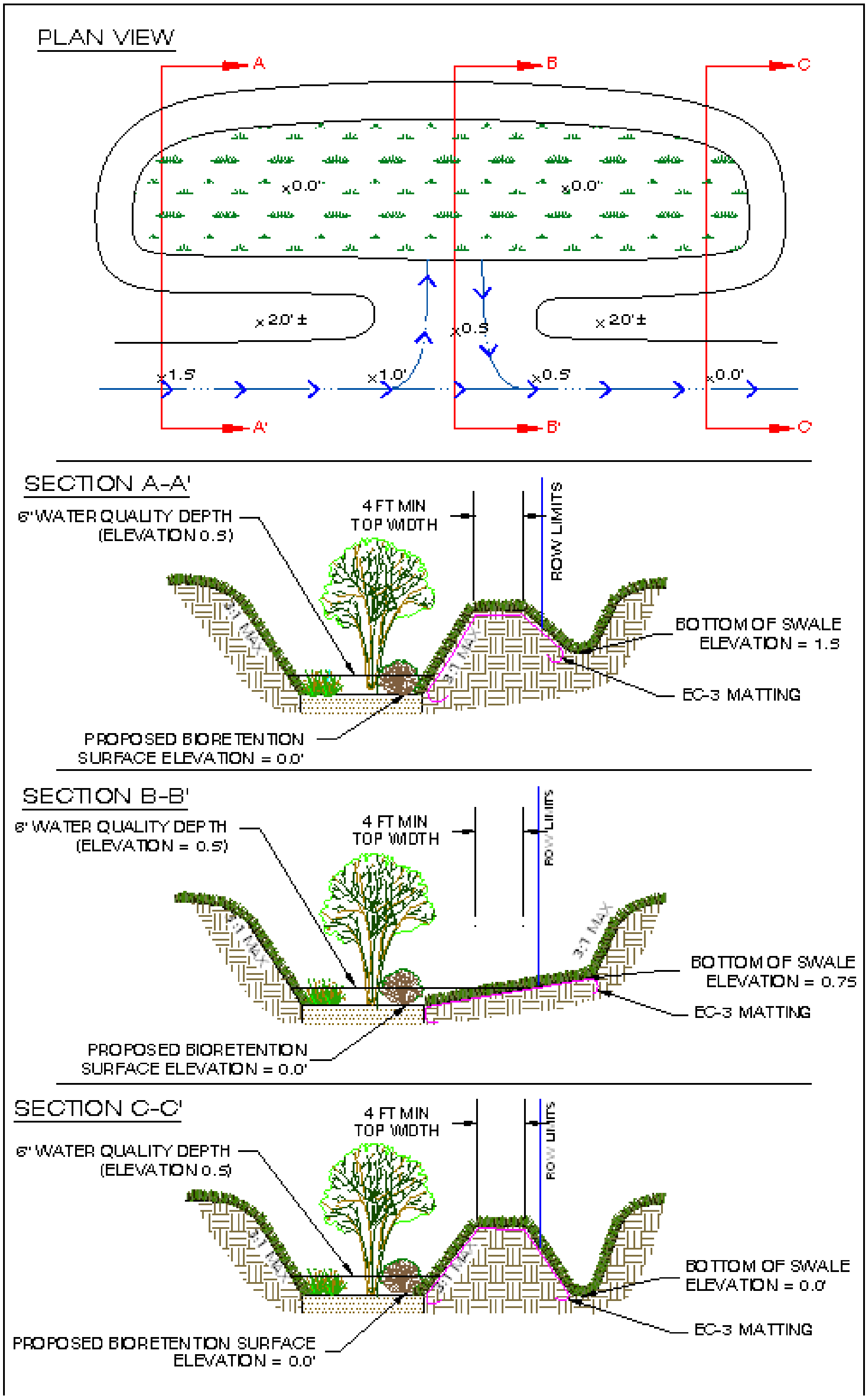

Figure 11.4. Simple Off-Line BMP

11.6 WATER QUANTITY CONTROL

The water quantity control requirements of the VSMP regulations have evolved as described in **Section 10.1.3** of **Chapter 10** of this Handbook**.** The VSMP regulations divide the quantity control requirements into Channel Protection criteria and Flood Protection criteria.

With the adoption of the new VSMP regulations, there is a possibility for confusion, since there are multiple active performance criteria and technical requirements for channel protection currently in place, as follows:

1. **Minimum Standard 19** of the Erosion and Sediment Control Regulations (**4 VAC 50-30-40.19**). This criterion is currently applied statewide on all regulated land disturbing activities.

2. Stream channel erosion provisions (**4 VAC 50-60-97)** of Part II.C of the VSMP regulations. This criterion is currently applied on all regulated land disturbing activities in jurisdictions that implement the VSMP regulations as adopted in 1999. This provision requires compliance with either Minimum Standard 19 or an alternate 1-year 24-hour storm extended detention standard. This standard may also apply to "grandfathered" development projects as defined by the VSMP regulations and determined by the VSMP authority.

3. Stream channel erosion provisions of **§10.1-603.4.A.7** of the *VSMA* and **§10.1-561.A** of the *VESCL*. This criterion was originally adopted in 2004 as a "safe harbor" for development projects that proposed a stormwater discharge to an eroded channel. The "safe harbor" was considered necessary to address a provision in Minimum Standard 19 that requires that all stormwater discharges must be to an adequate channel (and an eroded channel was considered, by definition, to be *not* adequate, regardless of on-site detention or volume reduction).

   Implementation of the criterion of this "safe harbor" provision outlined below *exempts the applicant from any flow rate capacity and velocity requirements for natural or man-made channels as defined in any regulations promulgated pursuant* the Virginia SWM or ESC laws and associated regulations.

   The technical criterion of this "safe harbor" provision includes:
   i) *Detain the **water quality volume** and release it over 48 hours;*
   ii) *Detain and release over a 24-hour period the expected rainfall resulting from the **one year, 24-hour storm**; and*
   iii) *Reduce the allowable peak flow rate resulting from the **1.5, 2**, and **10-year, 24-hour storms** to a level that is less than or equal to the peak flow rate from the site assuming it was in a good forested condition, achieved through multiplication of the forested peak flow rate by a reduction factor that is equal to the runoff volume from the site when it was in a good forested condition divided by the runoff volume from the site in its proposed condition.*

This criterion provided the groundwork for the development and ultimate adoption of the Channel Protection criteria in 4 VAC 50-60-66 of the current VSMP regulations (VSMP Channel Protection Criteria). The intention is to eventually replace the MS-19 provisions of the

Erosion and Sediment Control Regulations with the VSMP Channel Protection Criteria (item 2 above) in an effort to have a single technical standard for stream channel protection. It is also expected that the "safe Harbor" provisions will be eliminated since the VSMP Channel Protection Criteria addresses the storms that are considered to cause most of the channel erosion without the unnecessarily large storage volumes required to address the larger and less frequent storms.

Therefore, this section will only cover the provisions of the VSMP Channel Protection Criteria. Information on compliance with MS-19 criterion can be found in the **Chapter 5** of the ***Blue Book***, and the information provided here, in addition to the hydraulic calculations in **Chapter 5** of the ***Blue Book,*** should be sufficient for applicants interested in implementing the "safe harbor" criteria.

11.6.1 VSMP Channel Protection Criteria

The VSMP Channel Protection Criteria establish the requirements for discharges of stormwater to one of three types of channels, specifically referred to as "*Stormwater Conveyance Systems*" which are defined in the VSMP regulations (**4 VAC 50-60-10**) as a combination of drainage components that are used to convey stormwater discharge, either within or downstream of the land-disturbing activity as follows:

*(i) "**Manmade stormwater conveyance system**" means a pipe, ditch, vegetated swale, or other stormwater conveyance system constructed by man except for restored stormwater conveyance systems;*

*(ii) "**Natural stormwater conveyance system**" means the main channel of a natural stream and the flood-prone area adjacent to the main channel* (**Note:** emphasis added)*; or*

*(iii) "**Restored stormwater conveyance system**" means a stormwater conveyance system that has been designed and constructed using natural channel design concepts. Restored stormwater conveyance systems include the main channel and the flood-prone area adjacent to the main channel.*

The following are excerpts from the VSMP Channel Protection Criteria (**4 VAC 50-60-66 B**):

1. ***Manmade Stormwater Conveyance System (4 VAC 50-60-66 B 1).*** *When stormwater from a development is discharged to a manmade stormwater conveyance system, following the land-disturbing activity, either:*
   a. *The Manmade Stormwater Conveyance system shall convey the post-development peak flow rate from the two-year 24-hour storm event without causing erosion of the system. Detention of stormwater or downstream improvements may be incorporated into the approved land-disturbing activity to meet this criterion, at the discretion of the stormwater program administrative authority; or*
   b. *The peak discharge requirements for concentrated stormwater flow to natural stormwater conveyance systems in subsection 3 (Natural Stormwater Conveyance Systems) shall be met.*

Subdivision (a) indicates that a stormwater detention system may be incorporated into the site design such that the outflow does not cause erosion of the system. A manmade conveyance system can consist of various channel lining materials that will have different maximum allowable velocities: grass, grass with permanent stabilization matting, rip rap, or other material. The VESCH (latest edition) provides information on the allowable velocity for various natural materials. The designer should refer to manufacturer specifications for manufactured permanent or temporary stabilization products.

> **NOTE**: Temporary stabilization products are intended to temporarily support the soil and vegetative growth until full stabilization is achieved. However, the design must address the occurrence of erosive peak flows prior to the establishment of the vegetation.

Subsection (b) refers to a new version of a “safe harbor”, meaning the designer can choose to implement the criteria required in item 3 of this section and that is deemed adequate to meet the criteria for any downstream conveyance system.

2. ***Restored Stormwater Conveyance Systems (4 VAC 50-60-66 B 2)***. *When stormwater from a development is discharged to a restored stormwater conveyance system that has been restored using natural design concepts, following the land-disturbing activity, either:*
   a. *The development shall be consistent, in combination with other stormwater runoff, with the design parameters of the restored stormwater conveyance system that is functioning in accordance with the design objectives; or*
   b. *The peak discharge requirements for concentrated stormwater flow to natural stormwater conveyance systems in subsection 3 shall be met.*

This standard requires that the designer verify that the restored stormwater conveyance system was designed to accommodate the stormwater discharge from the subject development, as well as “other stormwater runoff”, meaning the discharges from other new or existing developments. The primary goal is to ensure that the restored stormwater conveyance system is adequate and will not be impacted by the new stormwater discharge.

Similar to subsection 1, a stormwater detention system may be incorporated into the site design so that the outflow does not exceed the design capacity of the restored system for the designated design storms. Also similar to subsection 1, the safe harbor provision of compliance with criteria of subsection 3 is available if the discharge is not consistent with the design parameters of the restored system.

3. ***Natural Stormwater Conveyance Systems (4 VAC 50-60-66 B 3)***. *When stormwater from a development is discharged to a natural stormwater conveyance system, the maximum peak flow rate from the one-year 24-hour storm following the land-disturbing activity shall be calculated either:*

   a. *In accordance with the following methodology:*

$$Q_{Developed} \leq I.F.* (Q_{Pre\text{-}developed} * RV_{Pre\text{-}Developed})/RV_{Developed}$$

*Under no condition shall $Q_{Developed}$ be greater than $Q_{Pre\text{-}Developed}$ nor shall $Q_{Developed}$ be required to be less than that calculated in the equation (Q_{Forest} * RV_{Forest})/$RV_{Developed}$; Where:*
I.F. (Improvement Factor) equals 0.8 for sites > 1 acre or 0.9 for sites ≤ 1 acre.
$Q_{Developed}$ = *allowable peak flow rate of runoff from the developed site.*
$RV_{Developed}$ = *volume of runoff from the site in the developed condition.*
$Q_{Pre\text{-}Developed}$ = *peak flow rate of runoff from the site in the pre-developed condition.*
$RV_{Pre\text{-}Developed}$ = *volume of runoff from the site in pre-developed condition.*
Q_{Forest} = *peak flow rate of runoff from the site in a forested condition.*
RV_{Forest} = *volume of runoff from the site in a forested condition; or*

b. In accordance with another methodology that is demonstrated by the VSMP Authority to achieve equivalent results and is approved by the board.

The criterion for this subsection has been referred to as the "Energy Balance" method. While technically not "energy", the use of the peak discharge ($Q_{Developed}$) and the volume ($RV_{Developed}$) of the post-development runoff attempts to address the impact of the increased erosive energy of the stormwater runoff caused by the increase in peak discharge *and* volume of runoff. [The increased volume of runoff released from the development site results in a longer duration of discharge. Incorporating the time function associated with the increased volume more accurately reflects the "power" of the runoff discharging from the site in its developed condition, rather than energy (WSSI 2011b)]. This also establishes the framework for incorporating the volume reduction credit applied to the water quality *Tv*.

Figure 11.5 represents the theoretical discharge hydrographs in the post-development condition, as provided to the VSMP regulation Regulatory Advisory Panel (RAP). The *Post-development Conventional SWM* peak rate of discharge has been throttled down with a detention facility to replicate the peak discharge of the pre-development condition; however, the volume of runoff (the area under the runoff curve) is significantly greater than that of the pre-development condition. Thus the product of the peak rate and the volume is greater than that of the pre-development condition. The *Post-development Energy Balance* discharge hydrograph reflects a significantly reduced peak discharge to compensate for the increased volume. As such, the basis of the Energy Balance is to achieve the goal of the post-development "energy" being equal to (or less than) the pre-development energy. The "energy" for the purposes of the VSMP regulation is defined as the peak flow rate multiplied by the volume of runoff. The "energy balance" of the pre- and post-development condition is defined as follows:

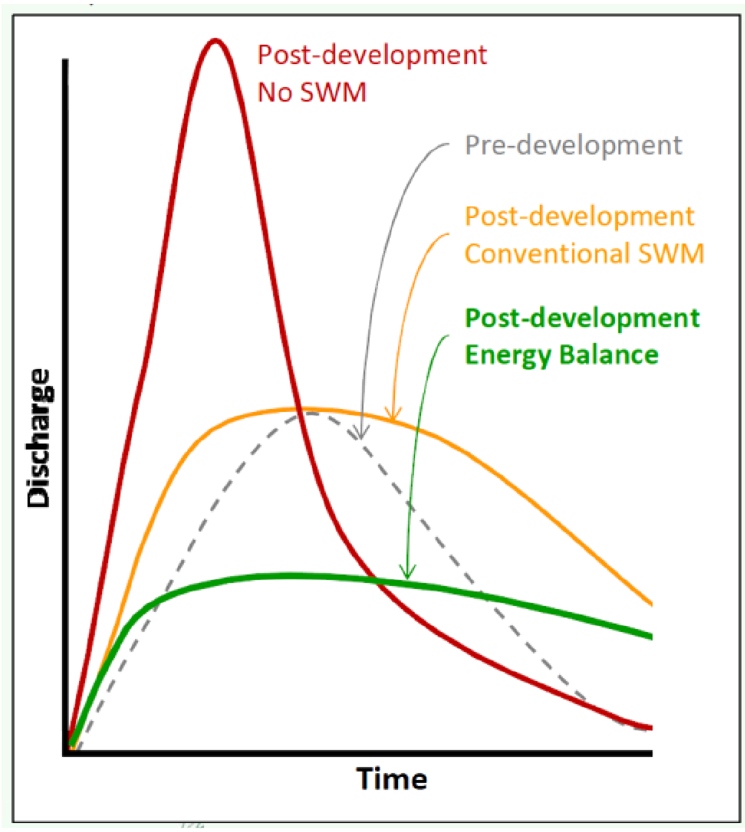

Figure 11.5. Theoretical Runoff and Discharge Hydrographs (Source: WSSI 2011b)

Equation 11.13. "Energy" Balance of Pre- and Post-Development Runoff Conditions

*Developed Condition Runoff (Peak Flow Rate * Volume)* ≤
*Pre-Developed Condition Runoff (Peak Flow Rate * Volume)*

Rearranging **Equation 11.13** to solve for the allowable *Developed Condition Runoff Peak Flow Rate* yields a reduction in the developed peak flow rate that is inversely proportional to the increase in runoff volume (**Equation 11.14** below).

In order to facilitate the NRCS *CN* computational methods, the terminology of the Energy Balance Method as expressed in Item 3 above **(4 VAC 50-60-66.B.3)** must be reviewed.

> **NOTE: Terminology Alert #6** – **Section 11.3.4** of this chapter identifies some of the terms that should be used with caution so as to not misrepresent any of the hydrologic parameters. This warning expands that caution to include the terminology of the VSMP Channel Protection Criteria. The term ***Q*** for the pre- and post-development conditions as defined in **4 VAC 50-60-66 B 3** is inconsistent with the traditional nomenclature of the NRCS Runoff Equation. All the related values are summarized in **Table 11.3** below. Unfortunately, the various computational methods use similar (and in some cases identical) terms to represent very different parameters. Designers should be very careful to ensure

the proper value (and corresponding unit) are being used for each designated parameter.

Table 11.3. Hydrology Terminology

Description	Units	Term
NRCS TR-55		
Runoff Depth	inches (in)	***Q***
Runoff Volume	cubic feet (ft^3) or acre feet (ac.ft.)	***Vr***
Storage Volume	cubic feet (ft^3) or acre feet (ac.ft.)	***Vs***
Peak Discharge	cubic feet per second (cfs)	q_p
VRRM Treatment Volume Runoff Coefficients		
Unit-less Volumetric Runoff Coefficients		***Rv***
VRRM Curve Number Adjustment		
Runoff Depth	inches	***RV***
VSMP Regulations Channel Protection Criteria (4VAC50-60-66.B)		
Runoff Volume*	cubic feet (ft^3) or acre feet (ac.ft.)*	***RV***

*Units of volume in the VSMP regulations Channel Protection Criteria can also be expressed in terms of *watershed-inches* or inches (consistent with Runoff Depth as expressed in the VRRM *CN* adjustment.

The VSMP regulation Channel Protection Criteria (or *Energy Balance Method*) defined in **4 VAC 50-60-66 B 3** and as expressed in narrative terms in **Equation 11.13** above is re-defined in **Equation 11.14** below, using the terminology of the NRCS TR-55 Runoff Equation as provided in **Table 11.3**, in order to maintain consistency with the traditional hydrologic nomenclature.

Another modification is the simplification of the Energy Balance Method term for the runoff volume. The ratio of the pre- and post-development condition runoff *volume* is more readily expressed as the ratio of pre- and post-development *runoff depth*. Both terms yield the same ratio, however the use of the runoff depth (this value is represented by ***Q*** in the NRCS terminology, and ***RV*** in the VRRM) greatly simplifies the computation and also facilitates the Curve Number adjustment: the term for the runoff depth, ***Q*** (or ***RV***), measured in inches, is a readily determined parameter in computing the TR-55 Graphical Peak Discharge, q_p**.** The Runoff Depth, ***Q***, (or ***RV***) is a function of rainfall and the drainage area *CN*, and can be determined using the NRCS Runoff Equation (**Equation 11.3** and TR-55 Equation 2-1), or read from the tables in **Appendix 11-C** of this Chapter, or read graphically from **Figure 11-C.1** (TR-55 2-1). **Equation 11.14** reflects this change, and the definitions of the terms reflect the use of runoff depth rather than volume.

Equation 11.14. VSMP Channel Protection Criteria: Energy Balance Method with NRCS Terminology

$$q_{pDeveloped} \leq I.F. * \left(q_{pPre-Developed} * Q_{Pre-Developed}\right)/Q_{Developed}$$

Or rewritten:

$$q_{pDeveloped} \leq I.F. * \left(q_{pPre-Developed} * RV_{Pre-Developed}\right)/RV_{Developed}$$

Where:
I.F. (Improvement Factor) = 0.8 for sites > 1 acre or 0.9 for sites ≤ 1 acre.
$q_{pDeveloped}$ = allowable peak flow rate of runoff from the developed site (cfs).
$q_{pPre-Developed}$= peak flow rate of runoff pre-developed condition (cfs).
$Q_{Pre-Developed}$ = $RV_{Pre-Developed}$= developed condition runoff depth (inches).
$Q_{Developed}$ = $RV_{Developed}$ = developed condition runoff depth (inches).

NOTE: The term $q_{pDeveloped}$ in **Equation 11.14** could be more accurately expressed as $q_{pAllowable}$ since it represents the allowable peak discharge from the developed site, and not the peak discharge into a proposed BMP.

The addition of an improvement factor (I.F.) in the VSMP Channel Protection Criteria is based on the statutory requirement that the VSMP regulations "*improve upon the contributing share of the existing predevelopment runoff characteristics and site hydrology if stream channel erosion or localized flooding is an existing predevelopment condition*. (§ 10.1-603.4.A.7, Code of Virginia). The improvement factor value of 0.8 for sites > 1 acre or 0.9 for sites ≤ 1 acre is established by the VSMP regulation.

11.6.2. VSMP Channel Protection Criteria: Allowable Peak Discharge Computations

The design storm for the VSMP Channel Protection Criteria is either the 2-year 24-hour design storm (for manmade stormwater conveyance system) or the 1-year 24-hour design storm (for discharge to a natural stormwater conveyance system. The design storm for the VSMP Channel Protection Criteria for restored stormwater conveyance systems will vary based on the design of the restored system. The hydrologic computations for determining the pre- and post-developed peak discharges for the various design storms, using the NRCS methods, are outlined **Sections 4-4.3** and **4-4.4** of **Chapter 4** in the ***Blue Book***. The following steps represent the procedure for applying the VSMP Channel Protection Criteria for the discharge of stormwater to a natural stormwater conveyance system (the 1-year 24-hour design storm) and will reference the ***Blue Book*** for certain hydrologic details rather than repeating them here.

The hydrology for the example development site in **Section 13.1** of **Chapter 13** will be used here to illustrate the Energy Balance computations.

Step 1: Pre- and Post Development Hydrology

Develop the basic hydrologic parameters for the Drainage Areas for both the pre- and post-development conditions. The VSMP regulation Water Quantity requirements are applied at each point of stormwater discharge from the site. So while the hydrology will be established for the entire site for water quality purposes, the designer must address water quantity requirements for each point of discharge. For this example, the Pre- and Post-development condition for **Drainage Area A** is analyzed as follows:

- The development of the *CN* and *Tc* are covered in detail in NRCS TR-55 and **Section 4.4.3** of **Chapter 4** of the ***Blue Book***.
- The development of the Graphical Peak Discharge is described in detail in TR-55 and **Section 4.4.4** of **Chapter 4** of the ***Blue Book***.

Step 2: Pre- and Post-Development Runoff Volume

The Pre- and Post-Development values for Q_1 in **Table 11.4** are substituted into **Equation 11.14** above for $Q_{Pre-Developed}$ and $Q_{Post-Developed}$ respectively, along with the Improvement Factor (I.F. = 0.8) as follows:

Table 11.4. Site Hydrology: Drainage Area A

Rainfall Depths: 1-year 24-hour storm: **2.66";** 10-year 24-hour storm: **4.93"**									
Pre-Developed DA A									
Land Use	**Condition**	**HSG**	**Area (ac)**	**CN**	**Tc (hrs)**	**Q_1 (in)**	**q_{p1} (cfs)**	**Q_{10} (in)**	**q_{p10} (cfs)**
Meadow	Good	B	2.05	58					
Meadow	Good	C	1.38	71					
Woods	Good	C	0.50	70					
		Total	**3.93**	**64**	**0.35**	**0.33**	**0.9**	**1.54**	**6.1**
Post-Developed DA A									
Land Use	**Condition**	**HSG**	**Area (ac)**	**CN**	**Tc (hrs)**	**Q_1 (in)**	**q_{p1} (cfs)**	**Q_{10} (in)**	**q_{p10} (cfs)**
Open Space	Good	B	2.05	61					
Open Space	Good	C	0.50	74					
Impervious		C	0.88	98					
Woods	Good	C	0.50	70					
		Total	**3.93**	**72**	**0.21**	**0.61**	**2.9**	**2.15**	**11.0**

Equation 11.15. Energy Balance Method with NRCS Terminology – Solved for $q_{pAllowable}$

$$q_{pAllowable} \leq I.F. * (q_{pPre-Developed} * Q_{Pre-Developed})/Q_{Developed}$$

$$q_{pAllowable} \leq 0.8 * (q_{pPre-Developed} * 0.33")/0.61"$$

$$q_{pAllowable} \leq 0.43 * (q_{pPre-Developed})$$

Note that the term for $q_{pAllowable}$ has been substituted for $q_{pDeveloped}$.

Step 3: Allowable Post-Development Peak Discharge

If the pre-development peak discharge for the 1-year 24 hour storm has not been calculated yet, that needs to be done next. **Table 11.4** conveniently provides both the pre-and post-development values, so the post development allowable peak discharge can now be computed by inserting the value for $q_{pPre-Developed}$ into the equation developed in Step 2 above.

$$q_{pAllowable} \leq \; 0.43 \;\; * (0.9\, cfs)$$

$$q_{pAllawable} \leq \; \mathbf{0.4\ cfs}$$

The 1-year post-development allowable peak discharge of 2.9 cfs (from **Table 11.4**) must be reduced to 0.4 cfs. **This reduction does not reflect the incorporation of any runoff reduction credits achieved in compliance with the water quality criteria (i.e., through BMPs).** The implementation of runoff reduction practices will reduce the developed condition runoff depth $Q_{Developed}$, which will serve to increase the calculated $q_{pAllowable}$.

Step 4: Determine the Minimum Peak Discharge

The VSMP Channel Protection Criteria (**4 VAC 50-60-66 B 3 a**) stipulates that:

- Under no condition shall the allowable developed condition discharge be greater than the pre-development discharge, and
- The allowable developed condition discharge shall not be required to be less than that of the pre-development condition reduced by the ratio of a forested condition to the Developed condition: $\left(q_{pForest} * Q_{Forest}\right)/Q_{Developed}$

The greater of the allowable discharges calculated in Step 3 and Step 4 above will govern as the developed condition allowable peak discharge.

11.6.3 Curve Number Adjustment for Large Storm Controls

An important element of the VRRM is the capability of the volume reduction practices to reduce the volume of runoff. In principle, when runoff reduction practices are used to capture and retain or infiltrate runoff, downstream stormwater management practices should not have to detain, retain or otherwise treat the volume that is removed. In other words, the volume of runoff reduction provided should be subtracted from the volume calculated by stormwater runoff peak flow computations. The challenge lies in how to accurately credit the *annual* volume reduction in the *single-event* computation of the peak rate of runoff from larger storms.

Peak flow rate reduction for single-event runoff and hydraulic routing models is accomplished by accounting for BMP stage-storage-discharge relationships. This computational procedure is outlined in detail in **Chapter 5** of the ***Blue Book***. Many of the BMPs used in the Runoff Reduction Method provide some amount of storage volume, and designers can apply basic hydraulic routing relationships to model the detention or retention of the runoff volume with respect to time. However, the response characteristics of many runoff reduction practices may not follow the traditional detention/retention design parameters. Routing of runoff reduction

BMPs can be a difficult and complex task, given all the hydrologic and hydraulic variables associated with volume reduction, such as evapotranspiration, storage within the soil media, infiltration, and extended filtration.

Several methods for manipulating the post-development condition runoff hydrograph were considered: Truncated Hydrograph, Hydrograph Scalar, Multiplication, Precipitation Adjustment (subtract retention from rainfall), Runoff Adjustment (subtract retention from runoff), and *CN* adjustment. (Koch, 2005) The Runoff Reduction Method uses the *CN* adjustment as a simple and conservative method for crediting specific runoff reduction values toward peak flow reduction. The method converts the total *annual* runoff reduction credit from all the BMPs in the drainage area from cubic feet (or acre-feet) to watershed-inches of retention storage, and then uses the NRCS TR-55 runoff equations 2-1 through 2-4 provided in *Urban Hydrology for Small Watersheds* (USDA 1986) to derive a Curve Number adjustment that reflects the reduced runoff depth. This new *CN* can then be used for computing the large storm peak discharge from the drainage area for determining the storage volume needed for downstream channel or flood protection requirements.

A simplified derivation of the computational procedure starts with the combined NRCS TR-55 Runoff Equations 2-1 through 2-4 in order to express the runoff depth in terms of rainfall and potential maximum retention. In addition, the potential maximum retention, S, is related to soil and cover conditions of the watershed through the *CN*, as described by **Equations 11.3** through **11.6** (TR-55 Eq. 2-1 thru 2-4), repeated here for purposes of this Section.

Equation 11.3 NRCS Runoff Equation, Q *[TR55 Eq. 2-1]*

$$Q = \frac{(P - I_\mathrm{a})^2}{(P - I_\mathrm{a}) + S}$$

Equation 11.4 NRCS Runoff Equation, Ia *[TR55 Eq. 2-2]*

$$I_\mathrm{a} = 0.2S$$

Equation 11.5 Modified NRCS Runoff Equation *[TR55 Eq. 2-3]*

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

Equation 11.6 NRCS Runoff Equation: S *[TR55 Eq. 2-4]*

$$S = \frac{1000}{CN} - 10$$

Where:

Q = runoff depth (in),
P = rainfall depth (in),
I_a = Initial abstraction (in),
S = potential maximum retention after runoff begins (in),
CN = Curve Number

The retention storage depth equivalent to the Runoff Reduction values assigned by the Runoff Reduction Method, and any additional retention storage provided on the site (expressed in terms of retention storage *R*, inches) is subtracted from the total runoff depth associated with the *CN* for the developed condition, which then will provide for a new value of S (Modified Equation 2-3). A new *CN* is then back-calculated from the new value of S using Equation 2-4 (Koch, 2005).

While it is not easy to predict the absolute runoff hydrograph modification provided by reducing stormwater runoff volumes, it is clear that reducing runoff volumes will have an impact on the runoff hydrograph of a development site. Simple routing exercises verify that this Curve Number adjustment approach represents a conservative estimate of peak reduction.

It is important to note that the Curve Number adjustment associated with the retention of one watershed-inch of runoff volume will decrease as the rainfall depth increases (meaning 1-inch of volume reduction has less of an impact on a 5-inch rain event than it will on a 2-inch rain event). Therefore, the *CN* adjustment must be computed for each design storm depth. This Curve Number adjustment procedure is simplified for designers in the VRRM Compliance Spreadsheet on the Channel and Flood Protection tab.

Equation 11.16: Modified Equation 11.3 NRCS Runoff Equation, Q
[TR55 Eq. 2-1] ***for Retention Storage***

$$Q - R = \frac{(P - 0.2S)^2}{(P + 0.8S)}$$

Where:
Q = runoff depth (in),
R = Retention Storage
P = rainfall depth (in),
S = potential maximum retention after runoff begins (in),
CN = Curve Number

Continuing the Channel Protection Criteria computations from above, the designer should have already developed the BMP implementation strategy for the drainage area in order to move on to the *CN* adjustment. This design continues to develop Drainage Area A from **Section 11.6.2** above, referring to **Example 13.1** of **Chapter 13** of this Handbook.

Step 5: Retention Volume Provided in Runoff Reduction BMPs.

This example, detailed in **Section 13.1** of **Chapter 13**, includes a combination of practices: a Vegetated Filter Strip, Permeable Pavement Level 1, and Bioretention Level 2. The total volume of runoff reduction credited in this drainage area is 2,631 ft^3 and is displayed in the VRRM Compliance Spreadsheet in the DA A tab, cell I77, and in the Channel and Flood Protection tab, cell C6.

Step 6: Curve Number Reduction

The Channel and Flood Protection tab displays the **Weighted *CN*** for the drainage area in cell G35 based on the standard *CN* definitions for *Forest/Open Space* (assumed to be consistent with TR-55's *woods* – even if the land cover is meadow or other land cover protected as open space), *Managed Turf*, and *Impervious Cover*.

For this example, before considering any runoff reduction, the weighted *CN* = 72, which is the same as the TR-55 *CN* as provided in **Table 11.4** above.

Table 11.5 below provides the runoff depth in inches, with and without Runoff Reduction, derived from the Channel and Flood Protection tab of the VRRM Compliance Spreadsheet.

Table 11.5. Curve Number Adjustment from the VRRM Compliance Spreadsheet Channel and Flood Protection Tab

	1-year storm	2-year storm	10-year storm
$RV_{Developed}$ (in) with no Runoff Reduction	0.61	0.94	2.14
$RV_{Developed}$ (in) with Runoff Reduction	0.43	0.76	1.96
Adjusted CN	**67**	**68**	**70**

NOTE: Terminology Alert #7 – The VRRM Compliance Spreadsheet calculates the *CN* adjustment in the Channel and Flood Protection tab using the Runoff Depth, ***RV***, in units of inches, which is the same parameter as the TR-55 Runoff Depth, ***Q***, in inches.

The computational procedure mimics **Equations 11.3** through **11.6**, and can be computed graphically by using **Figure 11.6** below with a rainfall depth P = 2.66 inches, and a Direct Runoff Depth, Q (or in the VRRM terminology, *RV*) = 0.41 inches. The intersection of the two values corresponds to a *CN* of 67. The use of **Figure 11.6** may lead to some error in the scale and accuracy of plotting the values of rainfall and runoff, and reading the *CN*, so the designer may elect to simply use the Channel and Flood Protection tab of the VRRM Compliance Spreadsheet. Likewise, there will be situations where a computed value for the RV or other values in the spreadsheet may vary slightly due to rounding or interpolation. The VRRM Spreadsheet selects nearest values when solving for S and back-calculating the adjusted *CN*.

Step 7: Re-compute the developed peak discharge for the 1-year 24-hour storm ($q_{p1Developed}$).

The designer should refer to **Section 4.4.4** of **Chapter 4** of the ***Blue Book*** (or TR-55) for guidance on calculating the peak discharge: Rainfall depth = 2.66 inches, *Tc* = 0.21 hours; and a *CN* = 67.

The new Peak Discharge is computed as 1.6 cfs. Therefore, the application of runoff reduction practices resulted in a runoff reduction credit of 2,631 ft^3, a *CN* reduction from 72 to 67 for the 1-year 24-hour rainfall, and a corresponding reduction in the 1-year peak discharge from 2.9 cfs to 1.6 cfs. These values are summarized in **Table 11.6**.

Table 11.6. Updated Site Hydrology for Drainage Area A, Developed Condition

	CN	q_{p1} (cfs)	RV_1 (inches)
Pre-Developed	64	0.9	0.33
Developed	72	2.9	0.62
Developed with Runoff Reduction (RR)	67	1.6	0.42

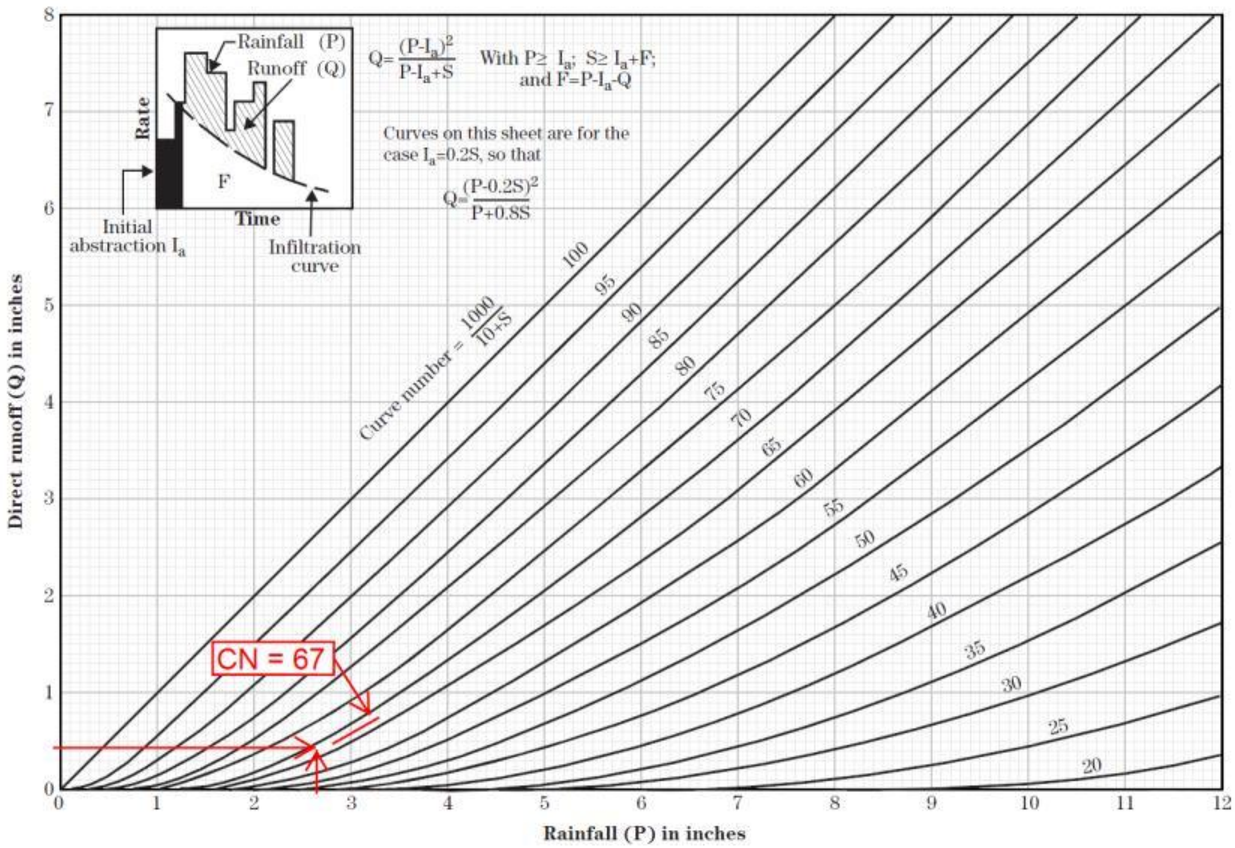

Figure 11.6. Solution of Runoff Equation (TR55, Figure 2-1)

Step 8: Calculate the Adjusted Allowable Peak Discharge (repeat of Steps 2 and 3 above with the new Site Hydrology using ***Equation 11.15: Energy Balance Method with NRCS Terminology – Solved for $q_{pAllowable}$***:

$$q_{p1Allowable} \leq I.F. * \left(q_{p1Pre-Developed} * RV_{1Pre-Developed}\right) / RV_{1Developed\ w\ RR}$$

$$q_{p1Allowable} \leq 0.8 * (0.9 * 0.33") / 0.43"$$

$$q_{p1Allowable} \leq \mathbf{0.6\ cfs}$$

NOTE: The value for $Q_{Pre-Developed}$ in **Equation 11.14** is replaced with the equivalent VRRM terminology: RV_1.

Note that the allowable peak discharge has increased, thereby reducing the required storage volume.

11.6.4 Storage Volume Computations

Several different options are available to the designer for calculating the storage volume required to reduce the developed peak discharge down to the allowable peak discharge. **Chapter 5** of the ***Blue Book*** discusses four different computational tools:

- Graphical Hydrograph Analysis;
- TR-55 Storage Volume for Detention Basins (Shortcut Method);
- Modified Rational Method Critical Storm Duration; and
- Modified Rational Method Critical Storm Duration, Direct Solution

The *Modified Rational Method Critical Storm Duration, Direct Solution* will require updated A, B Constants in order to solve for the storm that requires the greatest storage volume, and the *Modified Rational Method Critical Storm Duration* and the *Graphical Hydrograph Analysis* are not very practical without supporting computer software to simplify the computational process. Therefore, this Chapter will address the computational procedure using the TR-55 Storage Volume for Detention Basins (Shortcut Method), covered in **Section 5-4.2** of **Chapter 5** of the ***Blue Book***. (This procedure is also available in various computer program formats.)

Step 9: Calculate the Storage Volume required to achieve the allowable peak discharge *with* runoff reduction credits:

The information required for the TR-55 Short cut method from **Table 11.6** and **Equation 11.15** above:

$q_{p1Allowable}$ = 0.6 cfs

$q_{p1Developed}$ = 1.6 cfs

$Q_{1Developed} = RV_1$ = 0.43 inches

Using **Figure 11.7** below and the ratio of the allowable peak discharge to the peak inflow:

$$\left({}^{q_o}/_{q_i}\right) \text{ or } \left({}^{q_{p1Allowable}}/_{q_{p1Developed}}\right) = \left({}^{0.6\ cfs}/_{1.6\ cfs}\right) = 0.38$$

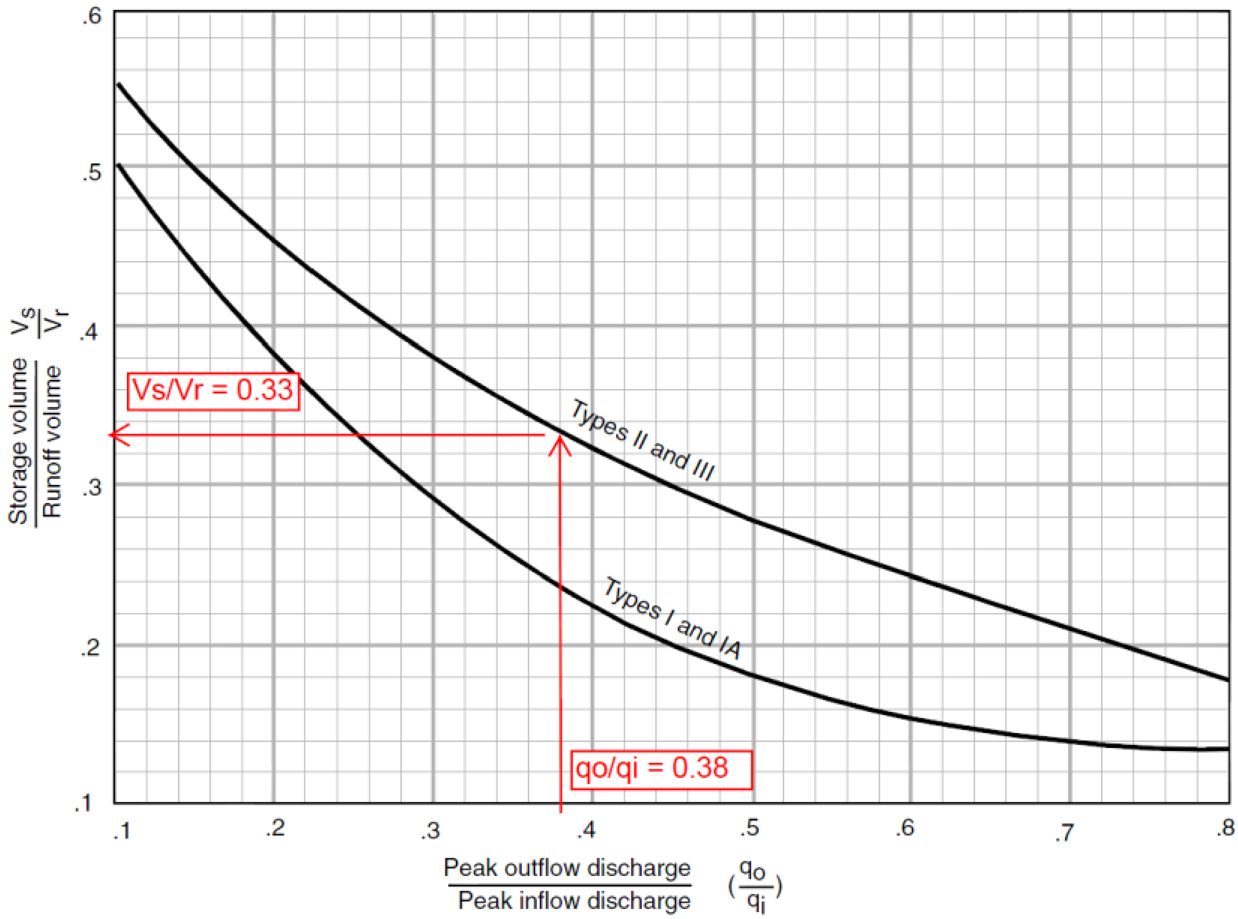

Figure 11.7. TR55 Detention Basin Routing *(USDA 1986)*

Read the ratio of the volume of storage to the volume of runoff from **Figure 11.7**:

$$^{Vs}/_{Vr} = 0.33$$

Solve for *Vs*: $Vs = Vr * \left(^{Vs}/_{Vr}\right)$

Where:

Vs = volume of storage required

Vr = developed condition runoff depth, in watershed-inches, expressed as Q or in the VRRM as RV_1 (step 9 above) = 0.43 watershed-inches

$^{Vs}/_{Vr}$= 0.33 from **Figure 11.7**

$$Vs = Vr * 0.33 = 0.43 * 0.33 = 0.14 \text{ watershed inches}$$

0.14 watershed inches * 3.93 ac * (3,630 ft^3/ac-in) = **1,997 ft^3** of storage required.

The benefits of using runoff reduction practices can be demonstrated by calculating the storage that would be required without any runoff reduction credits and comparing the result.

Repeat **Step 9** above with the following values:

Step 9: Calculate the Storage Volume required to achieve the allowable peak discharge ***without*** runoff reduction credits:

$q_{p1Allowable}$ = 0.4 cfs (**Steps 2** and **3** – no runoff reduction)

$q_{p1Developed}$ = 2.9 cfs (**Table 11.6**)

$Q_{1Developed} = RV_1$ = 0.62 inches (**Table 11.6**)

Using **Figure 11.7** and the ratio of the allowable discharge out to the discharge in:

$$\left({}^{q_o}/_{q_i}\right) \text{ or } \left({}^{q_{p1Allowable}}/_{q_{p1Developed}}\right) = \left({}^{0.4\ cfs}/_{2.9\ cfs}\right) = 0.14$$

From **Figure 11.7**: ${}^{Vs}/_{Vr}$ = 0.51

Solve for Vs: $Vs = Vr * \left({}^{Vs}/_{Vr}\right) = Vr * 0.51 = 0.62 * 0.51 = 0.32$ watershed-inches

0.32 watershed inches * 3.93 ac * (3,630 ft^3/ac-in) = **4,565 ft^3** of storage required.

The implementation of Runoff Reduction Practices can significantly reduce the total storage volume required to achieve the allowable release rate for the VSMP Channel Protection Criteria. In this example, the channel protection storage requirement was reduced from **4,565 ft^3** to **1,997 ft^3** (more than a 50% reduction). The VRRM provides a double reduction as an incentive to reduce the developed condition runoff volume and more closely replicate the site's pre-development hydrologic response, as follows:

1. The VSMP Channel Protection "Energy Balance" criteria allows an increase in the $q_{p1Allowable}$ (approaching the $q_{p1Pre-Developed}$), as the developed condition runoff volume is decreased by runoff reduction practices, more closely replicating the pre-development runoff volume; and
2. The VRRM *CN* Adjustment reduces the developed condition peak discharge ($q_{p1Developed}$).

Considering the example above, it is conceivable that the retention storage provided in the runoff reduction BMPs listed in **Step 5** and discussed in **Section 13.1** of Chapter **13** can be increased to provide the additional 1,997 ft^3 of storage, along with a hydraulic control structure (if needed) to ensure that the peak rate of discharge is not exceeded, thereby eliminating the need for a separate runoff quantity control detention facility.

11.6.5 VSMP Flood Protection Criteria

The same calculation procedures can be used to credit the retention storage towards the VSMP Quantity Control requirements (**4 VAC 50-60-66 C Water Quantity**). The relative influence of the retention storage towards adjusting the *CN* and the reducing the developed condition peak discharge (q_{p10}) decreases as the depth of rainfall increases. The 1-year 24-hour storm *CN* adjustment (from a *CN* of 72 to a *CN* of 67) is reduced for the 10-year 24-hour storm to a *CN* of 70.

However, the Flood Control criterion allows the designer to establish the required peak flow rate based on the capacity of the conveyance system, or based on the pre-development condition for those systems that experience flooding, and therefore may not need a significant reduction:

4 VAC 50-60-66 C. Water quantity

C. Flood protection. Concentrated stormwater flow shall be released into a stormwater conveyance system and shall meet one of the following criteria as demonstrated by use of acceptable hydrologic and hydraulic methodologies:

1. Concentrated stormwater flow to stormwater conveyance systems that currently do not experience localized flooding during the 10-year 24-hour storm event: The point of discharge releases stormwater into a stormwater conveyance system that, following the land-disturbing activity, confines the postdevelopment peak flow rate from the 10-year 24-hour storm event within the stormwater conveyance system. Detention of stormwater or downstream improvements may be incorporated into the approved land-disturbing activity to meet this criterion, at the discretion of the stormwater program administrative authority.

2. Concentrated stormwater flow to stormwater conveyance systems that currently experience localized flooding during the 10-year 24-hour storm event: The point of discharge either:

a. Confines the postdevelopment peak flow rate from the 10-year 24-hour storm event within the stormwater conveyance system to avoid the localized flooding. Detention of stormwater or downstream improvements may be incorporated into the approved land-disturbing activity to meet this criterion, at the discretion of the stormwater program administrative authority; or

b. Releases a postdevelopment peak flow rate for the 10-year 24-hour storm event that is less than the predevelopment peak flow rate from the 10-year 24-hour storm event. Downstream stormwater conveyance systems do not require any additional analysis to show compliance with flood protection criteria is this option is utilized.

The pre-development and developed design storm runoff depth (Q, or RV), in inches, and peak discharge (q_{p10}), in cfs, is calculated using the same method as described for Channel Protection in this Chapter, and in **Chapters 4 and 5** of the ***Blue Book***. The retention volume credit from the implementation of runoff reduction practices can be solved graphically or by reading the new *CN* from the Channel and Flood Protection tab of the VRRM Compliance Spreadsheet.

11.6.6 Limits of Analysis

Similar to the previous stormwater regulations, the VSMP Quantity Control criteria includes provisions that establish how far downstream the designer must analyze the stormwater conveyance system to demonstrate compliance. For the VSMP Channel Protection Criteria (**4 VAC 50-60-66 B 4**):

- If the VSMP Channel Protection criteria for *Natural Stormwater Conveyance Systems* is used, there is no requirement for a downstream analysis;
- If the VSMP Channel Protection criteria for *Manmade* or *Restored Stormwater Conveyance Systems* is used, then the stormwater conveyance systems shall be analyzed for compliance to a location that:
  - Based on land area, the point of discharge contributing drainage area is less than or equal to 1.0% of the total watershed area [draining to that point]; or
  - Based on peak flow rate, the peak flow rate from the one-year 24-hour storm at the point of discharge is less than or equal to 1.0% of the existing peak flow rate from the one-year 24-hour storm prior to the implementation of any stormwater quantity control measures.

The VSMP Flood Protection criterion (**4 VAC 50-60-66 C 3**) similarly establishes a limit of analysis when determining capacity of the stormwater conveyance system for the 10-year storm.

- If the point of discharge complies with the criteria for releasing the developed 10-year 24-hour storm peak discharge at below the pre-development rate, then no downstream analysis is required.
- If the point of discharge of the 10-year 24-hour storm is proposed to be contained within the stormwater conveyance system, then an analysis of the system to ensure the discharge stays within the system must be conducted to a point where:
  - The site's contributing drainage area is less than or equal to 1.0% of the total watershed area draining to a point of analysis in the downstream stormwater conveyance system;
  - Based on peak flow rate, the site's peak flow rate from the 10-year 24-hour storm event is less than or equal to 1.0% of the existing peak flow rate from the 10-year 24-hour storm event prior to the implementation of any stormwater quantity control measures; or
  - The stormwater conveyance system enters a mapped floodplain or other flood prone area, adopted by ordinance, of any VSMP Authority.

11.7 DEVELOPMENT ON PRIOR DEVELOPED LAND

The stormwater quality requirements for development on prior developed land are defined in **4 VAC 50-60-63** (Water Quality Design Criteria Requirements), discussed in **Chapter 5**, and outlined below. The required load reduction is a percent reduction rather than a pollutant load calculated based on the existing developed condition. In addition, within the redeveloped site, any increase of *impervious cover* (if any) must be considered as new development and therefore requires a load reduction comparable to that of new development for the acreage of new impervious (0.41 lb/ac). Therefore, the required load reduction for redevelopment is the total load reduction computed for the two conditions: the redeveloped site plus the new impervious cover on the site.

The requirements for water quantity as outlined in **4 VAC 50-60-66** (Water Quantity) do not distinguish the difference between new and re-development. Rather, the channel and flood protection requirements are defined by the downstream *stormwater conveyance system*. These stormwater quantity requirements are applied to the development project regardless of the status as new development or redevelopment, and are discussed below and covered in detail in **Section 11.6** of this Chapter.

11.7.1 Water Quality Criteria for Development on Prior Developed Land

For the purposes of the stormwater criteria, ***prior developed land*** is defined as land that has been previously utilized for residential, commercial, industrial, institutional, recreation, transportation or utility facilities or structures. Therefore, any land disturbing activity on a site that meets this definition must comply with the requirements of **4 VAC 50-60-63 A 2**, as follows:

2. Development on prior developed lands.

- *a. For land-disturbing activities disturbing greater than or equal to one acre that result in no net increase in impervious cover from the predevelopment condition, the total phosphorus load shall be reduced at least 20% below the predevelopment total phosphorus load.*
- *b. For regulated land-disturbing activities disturbing less than one acre that result in no net increase in impervious cover from the predevelopment condition, the total phosphorus load shall be reduced at least 10% below the predevelopment total phosphorus load.*
- *c. For land-disturbing activities that result in a net increase in impervious cover over the predevelopment condition, the design criteria for new development shall be applied to the increased impervious area. Depending on the area of disturbance, the criteria of subdivisions a or b above, shall be applied to the remainder of the site.*
- *d. In lieu of subdivision c, the total phosphorus load of a linear development project occurring on prior developed lands shall be reduced 20% below the predevelopment total phosphorus load.*
- *e. The total phosphorus load shall not be required to be reduced to below the applicable standard for new development unless a more stringent standard has been established by a local stormwater management program locality.*

The same principles outlined in **Section 11.4** of this chapter for computing the pollutant load (for both the pre-development and post-development condition) apply to the compliance computations for development on prior developed land. The difference in the computations will be in determining the pollutant load reduction requirement based on the disturbance thresholds and the amount of additional impervious cover (if any), as outlined above. The following section provides a description of the steps for computing the load reduction requirement, while **Chapter 12** outlines the procedures for using the VRRM Compliance Spreadsheet for Development on Prior Developed Lands.

> **NOTE:** For simplicity, the term ***Redevelopment*** will be used for *Development on Prior Developed Land*. Likewise, the term ***VRRM Redevelopment Compliance***

Spreadsheet will be used to refer to the VRRM Compliance Spreadsheet for Development on Prior Developed Lands.

The general procedure for computing the load reduction requirement on redevelopment projects is applied to 2 general categories of redevelopment:

1. Redevelopment sites that ***do not*** result in net increase in impervious cover in the *post-development* (or post-redevelopment) land cover; and
2. Redevelopment sites that ***do*** result in a net increase in impervious cover in the *post-development* (or post-redevelopment) land cover.

A third category of project is linear development occurring on prior developed lands. In order for a development project to be subject to a load reduction requirement there must be a change in the land cover from the pre- to post-development (or post-redevelopment) condition (**Table 11.1**), or other hydrologic change such as grading or drainage infrastructure improvements. Linear development as defined in the VSMP Regulations can include a variety of activities that are linear in nature but may not necessarily reflect a land cover change, i.e., above and below ground utility installation. Therefore, it is important to consider the definitions of the land cover categories of **Table 11.1** in order to verify if a change occurs, or if a management practice can be used to offset the change. Detailed definitions and management practices applicable to the different land cover designations are provided in **Table 12.1** of **Chapter 12**.

The most common type of linear development that will require a load reduction is the construction of transportation infrastructure. Linear roadway projects that construct additional traffic lanes, new turn lanes or intersection improvements in urban areas, etc., are redevelopment projects that clearly include a net increase in impervious cover. However, the VSMP Regulations specifically require that these projects achieve a 20% load reduction below the predevelopment condition; the criterion for new development (the site-based load limit) is not applied to the new impervious cover.

Another important distinction for linear transportation projects is that of pavement maintenance, i.e., milling and repaving or otherwise maintaining the roadway surface and right of way. These activities maintain the original grade, alignment, and footprint of impervious cover and are generally considered maintenance and not subject to the stormwater management requirements.

11.7.1.1 Redevelopment Sites that Do Not Increase Impervious Cover

The first procedure described here is for the sites that do not result in a net increase in impervious cover. In general this scenario requires a load reduction such that the post-development load is either 10 or 20% lower (depending on the acreage of land disturbance; see Subdivision 2-a or 2-b of **4 VAC 50-60-63 A**) than the load from the land cover of the original site.

Step 1: Resource Mapping (see **Chapter 6**) and Environmental Site Assessment

The Resource Mapping and Environmental Site Assessment will ideally identify the available locations for runoff reduction and/or pollutant removal practices on redevelopment projects within the existing and proposed site infrastructure prior to establishing a final design and grading plan. At urban and ultra-urban redevelopment sites, the proposed micro-topography and resulting drainage divides can often be manipulated to direct runoff to these favorable locations without significant impacts to the overall site design.

The designer can implement the stormwater practices to achieve the load reduction requirement by treating the new, redeveloped, or existing site areas *within the limits of the project* (as defined by the project site). The project site should incorporate all of the disturbed area and proposed improvements (including existing buildings when being renovated), and any additional area of the site needed for vehicle access, material and equipment staging, and the construction of the stormwater BMPs.

Step 2: Site Hydrology & Pollutant Loads

1. Determine the *pre-development* land cover (forest/open space, managed turf, or impervious).
   The *pre-development* (or pre-redevelopment) land cover is defined as the land cover that exists at the time that plans for the land development of a tract of land are submitted to the VSMP authority. Where a development is phased, or where plan submittal and approval is broken down into steps such as demolition of existing structures, preliminary grading, or construction of roads or utilities, etc., the land cover at the time of the first item submitted establishes the pre-development conditions.
2. Determine the *post-development* land cover (forest/open space, managed turf, or impervious).
   The *post-development* (or post-redevelopment) land cover is defined as the land cover that reasonably may be expected or anticipated to exist after completion of the land development activity on a specific site (i.e., the land cover as defined by the approved plans for the redevelopment project).
3. Compute the *pre-development* and *post-development* Site *Rv* (**Equation 11.8**), *Tv* (**Equation 11.7**), and corresponding pollutant loads (**Equation 11.9**).
4. Compute the load reduction requirement using **Equation 11.17** for redevelopment projects that disturb one acre or more (land disturbance ≥ 1 acre: subdivision 2-a of **4 VAC 50-60-63 A**), or **Equation 11.18** for re-development projects that disturb less than one acre (land disturbance < 1 acre: subdivision 2-b of **4 VAC 50-60-63 A**):

Equation 11.17. Load Reduction Requirement for Redevelopment (≥ 1 acre of disturbance)

$$L_{reduction} = L_{Post-ReDevelopment} - L_{Pre-ReDevelopment}(1 - 0.2)$$

Where:

$L_{reduction}$ = Load reduction requirement (lb/yr)
$L_{Post-ReDevelopment}$ = Post-development (or post redevelopment) load (lb/yr)
$L_{Pre-ReDevelopment}$ = Pre-development (or pre redevelopment) load (lb/yr)

OR

Equation 11.18. Load Reduction Requirement for Redevelopment (< 1 acre of disturbance)

$$L_{reduction} = L_{Post-ReDevelopment} - L_{Pre-ReDevelopment}(1 - 0.1)$$

Where:

$L_{reduction}$	= Load reduction requirement (lb/yr)
$L_{Post-ReDevelopment}$	= Post-development (or post redevelopment) load (lb/yr)
$L_{Pre-ReDevelopment}$	= Pre-development (or pre redevelopment) load (lb/yr)

5. Verify that the load reduction requirement computed in item 4 does not exceed that which would be required to meet the load limit standard for new development (0.41 lb/ac):

Equation 11.19. Redevelopment Load Reduction Limit

$$L_{reduction} \leq L_{Post-ReDevelopment} - (0.41\, lb/ac/yr) \times A$$

Where:

$L_{reduction}$	= total load reduction requirement (lb) for the redevelopment project computed in Step 4
$L_{Post-ReDevelopment}$	= post-redevelopment pollutant load (**Equation 11.9**)
0.41 *lb/ac/yr*	= site based TP load limit
A	= redevelopment site area (acres)

NOTE: The VRRM Redevelopment Compliance Spreadsheet provides for these computations. The user must enter the *total disturbed acreage* and the *pre-development* and *post-development* land cover acres on the Site Data tab. The spreadsheet will compute the total load reduction requirement. Refer to **Section 12.4** of **Chapter 12** for the VRRM Redevelopment Compliance Spreadsheet user's guide.

Step 3: Drainage Area Hydrology, Peak Discharge, and Treatment Volume (Tv)

Repeat the procedures of Step 2 as needed to determine the post-development Land Cover and corresponding Site *Rv* (**Equation 11.8**) and *Tv* (**Equation 11.7**) in each drainage area.

Step 4: Apply volume (or load) reduction BMPs to the redevelopment site in order to achieve the required reduction calculated in Step 2 or by **Equation 11.10**, whichever is less.

11.7.1.2 Redevelopment Sites that Increase Impervious Cover

The following procedure is for re-development sites that result in a net increase in impervious cover in the post-development condition.

Step 1: Resource Mapping (see **Chapter 6**) and Environmental Site Assessment.

Step 2: Site Hydrology & Pollutant Loads

1. Determine the *pre-development* land cover (forest/open space, managed turf, or impervious).
2. Determine the *post-development* land cover (forest/open space, managed turf, or impervious).
3. Determine the *adjusted pre-development* land cover.
   The *adjusted pre-development* land cover is the pre-development land cover minus the pervious acreage (forest/open space or turf based on soil types) proposed for new impervious cover.
4. Determine a comparably adjusted *post-development* land cover.
   This is the *post-development* land cover minus the net acreage of new impervious cover.

   The *adjusted pre-development* land cover acreage is now the same as the post-development land cover, and is considered the redevelopment acreage used to compute the 10 or 20% load reduction requirement (**Equation 11.17** or **11.18** based on the acreage of disturbance.)

   The net acreage of increased impervious cover is considered new development and is used to compute the load reduction required to meet the load limit for new development (subdivision 2-c of **4 VAC 50-60-63 A**).
5. Compute the *pre-development*, *adjusted pre-development*, *post-development*, and *new impervious Rv* (**Equation 11.8**), *Tv* (**Equation 11.7**), and corresponding pollutant loads (**Equation 11.9**).

   NOTE: An *adjusted* pre- and post-development land cover is required in order to accommodate the computation of dual load reduction criteria for redevelopment sites with a net increase in impervious cover. The required total load reduction for the redevelopment site is the sum of the load reduction from these two computations:
   - The load reduction required for the new impervious cover to meet the site based load limit of 0.41 lb/ac/yr (**Section 11.4.4.2**); and
   - The load reduction required for the balance of the site to meet the 10 or 20% load reduction from that of the existing (pre-development) land cover.
6. Compute the new development area load reduction requirement for the net acreage of new impervious cover (**Equation 11.10**)
7. Compute the redevelopment area load reduction requirement using **Equation 11.17** for redevelopment projects that disturb one acre or more (land disturbance ≥ 1 acre;

subdivision 2-a of **4 VAC 50-60-63 A**), or **Equation 11.18** for redevelopment projects that disturb less than one acre (land disturbance < 1 acre; subdivision 2-b of **4 VAC 50-60-63 A**):

8. Add the load reduction requirements of Step 6 and Step 7 of this procedure for the total redevelopment site load reduction.
9. Verify that the load reduction requirement computed in item 8 does not exceed that which would be required to meet the load limit standard for new development (0.41 lb/ac) using **Equation 11.19**.

Step 3: Drainage Area Hydrology, Peak Discharge, and Treatment Volume (Tv)

Repeat the procedures of Step 2 as needed to determine the post-development Land Cover and corresponding Site *Rv* (**Equation 11.8**) and *Tv* (**Equation 11.7**) in each drainage area.

Step 4: Apply volume (or load) reduction BMPs to the redevelopment site in order to achieve the required reduction calculated in Step 2 or by **Equation 11.10**, whichever is less.

NOTE: The VRRM Redevelopment Compliance Spreadsheet provides for all of the computations listed in **Sections 11.7.1.1** and **11.7.1.2**. The user must enter the total disturbed acreage, and the *pre-development* and *post-development* land cover acres on the Site Data tab (reflecting the increase in impervious cover and the corresponding decrease in the pervious cover in the *post-development* land use). The spreadsheet will perform the computations for the two criteria and provide the total load reduction requirement. Refer to **Section 12.4** of **Chapter 12** for the VRRM Redevelopment Compliance Spreadsheet user's guide.

11.7.2 Water Quantity Criteria for Development on Prior Developed Land

The requirements for channel and flood protection on redevelopment projects are the same as those for new development and are a determined in part by the type of downstream *stormwater conveyance system* (**Section 11.6.1**: VSMP Channel Protection Criteria and **Section 11.6.5**: VSMP Flood Protection Criteria, derived from **4 VAC 50-60-66**). The criteria for both channel and flood protection include provisions that identify conditions in the downstream stormwater conveyance system (erosive velocity, out of bank flows or flooding, etc.) that in turn define the specific quantity control requirements.

Minimal increases in impervious cover may in turn require a minimal amount of volume or peak flow control to meet the requirements of a manmade or restored stormwater conveyance system (**4 VAC 50-60-66 B 1 and 2**). Similarly, application of the Energy Balance Method for discharge to a natural stormwater conveyance system when the net increase in impervious cover is minimal should yield an equally minimal flow reduction requirement based on similar pre- and post-development conditions. (Even no increase in impervious cover will require some flow reduction due to the Energy Balance Method Improvement Factor of 0.8). The application of a water quality BMP strategy to achieve the load reduction requirement (10% or 20%) may provide enough volume reduction (or be expanded as needed) such that the curve number adjustment or detention storage achieves required peak rate reduction.

In all cases, the designer should carefully analyze the receiving stormwater conveyance system in order to define the requirements, and select the appropriate BMP strategy that achieves both the quality (**Section 11.5**) and quantity requirements (**Section 11.6**).

11.8 REFERENCES

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